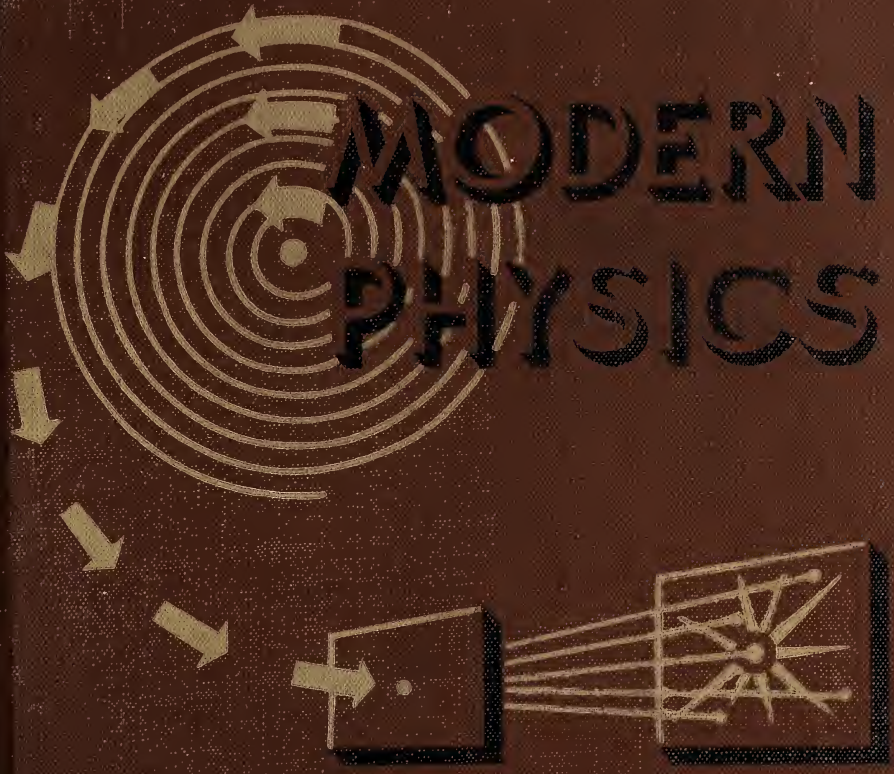
# MODERN PHYSICS



CHARLES E. DULL

rdon Kenney
B.R. 224
VCHS

Ron Guenolade
VCHS

D. G.

Ex libris
UNIVERSITATIS
ALBERTÆNSIS

The John S. Sandercock Library

Department of Educational Administration

The University of Alberta

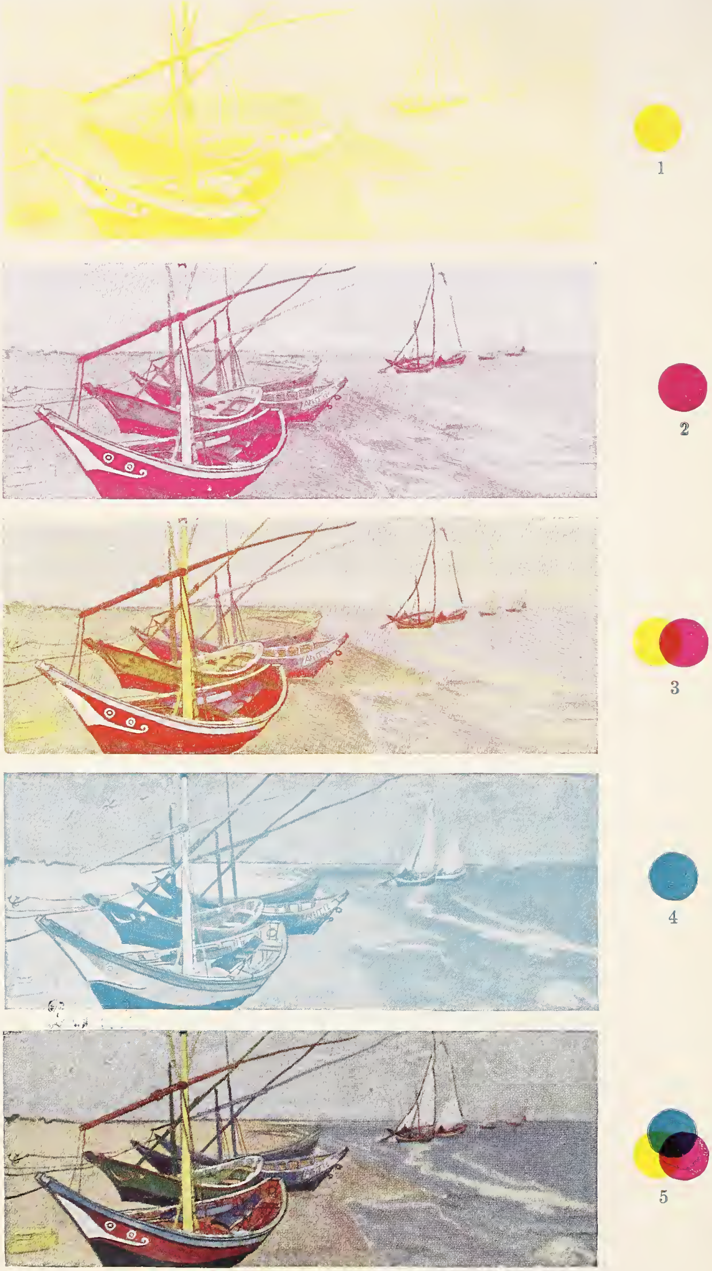
Edmonton, Alberta

T6G 2G5

JOHN S. SANDERCOCK
9523 - 81 STREET
EDMONTON 469-5571
T6C 2W4

Digitized by the Internet Archive
in 2017 with funding from
University of Alberta Libraries

https://archive.org/details/modernphysicsnew00dull



*Courtesy, Rudolf Lesch Fine Arts, Inc., New York City*

Three-color printing. 1. yellow plate; 2. red plate; 3. red on yellow; 4. blue plate; 5. yellow, red, and blue combined. Notice the various colors and shades in the finished print.

# MODERN PHYSICS

CHARLES E. DULL

*Head of Science Department, West Side High*
*School, and Supervisor of Science for the*
*Junior and Senior High Schools,*
*Newark, New Jersey*

*NEW EDITION*

001102

TORONTO

CLARKE, IRWIN & COMPANY LIMITED

COPYRIGHT, 1939, 1943, 1945
BY
HENRY HOLT AND COMPANY, INC.

COPYRIGHT, CANADA, 1945
BY
CLARKE, IRWIN & COMPANY LIMITED

*First Canadian Printing, 1945*
*Second Canadian Printing, 1946*

PRINTED IN CANADA

UNIVERSITY LIBRARY
UNIVERSITY OF ALBERTA

# Preface

Few subjects touch a person's life so closely as elementary physics. No subject is better fitted to develop the reasoning powers, or to stimulate that uncommon faculty known as "common sense." From the time the pupil opens the water faucet in the morning until he snaps off the electric switch upon retiring, he is constantly applying or observing some principle of physics. These principles may be connected with the airplane, the automobile, or television; they may have to do with the more prosaic wheelbarrows, bucksaws, or garden tools; or they may be related to football, baseball, or some other sport.

In the writing of this textbook, the author has practiced the following method of approach:

1. The topic is stated or a question is raised.
2. Some incident with which the pupil is familiar is used as an introduction.
3. The physical principle is then discussed or explained in language simple enough for a beginner to understand.
4. The manner in which the principle is utilized is shown by the use of one or more applications.

Such a method arouses interest by its inductive approach; it is understandable because of its simplicity; it links the principle with the pupil's former experiences; it is practical because it introduces so many appliances which the pupil meets from day to day.

Many of the illustrations are line diagrams. They are used abundantly because they generally prove to be better teaching aids than halftones. For example, one finds it difficult to explain the operation of a gas engine, a steam engine, or a dynamo from photographs. With a line drawing one can emphasize the important details. Halftones, which are also used abundantly, give a good idea of the magnitude and the scope of the machines used as applications of physical principles.

Many word illustrations are used, too. They make the book somewhat longer, but they make it more readable, and they serve to emphasize the fact that a so-called cold, logical science is rich in human interest. Many historical references are included for the same reason, lest the pupil get the idea that the science of physics is like Topsy, and "just grew." In several cases, the effect of the study of physics upon economic conditions is pointed out. Possibly the development of this science was one of the most important factors in the "Industrial Revolution." Physics is a science, too, which has an important bearing upon various safety factors.

The author defines density as the *weight* per unit volume, because he believes that a beginner is confused when he is asked to go into the laboratory, *weigh* an object, and then record its *mass*. His use of the term "specific weight" or "specific density" is not a mere whim. He has learned from years of experience that either term has more meaning to a beginner than the term "specific gravity." The time is more than ripe, too, for the changing of electrical-wiring diagrams to conform to the electron-flow theory. A Congress of Physicists should doubtless meet and agree to make such a change. Until they do, it would cause much confusion for one author to make such a change, particularly in schools where several different books are in use. In the meantime, we shall follow Franklin.

In the preparation of this textbook, the author has constantly tried to keep in mind the pupil's point of view. The language is simple, and the explanations are full enough to enable pupils to understand those topics which sometimes appear difficult. The book has all the material needed to meet College Entrance Examination Board requirements. It can be used, too, with non-college groups in differentiated courses.

Some topics are starred to indicate that they may be omitted; but the final selection is left to the instructor, who will find it easier to omit certain topics than to add new material.

Among the aids to pupils are the word illustrations and picture illustrations which have been mentioned. In addition, the pupil is given a glimpse of each Unit by the use of previews. At the beginning of each chapter, he will find a glossary of new terms. Every new type of mathematical problem is explained. In addition to the explanation, one problem is solved for the pupil. This not only insures a complete understanding of mathematical physics, but it also illustrates an analytical approach to problem solving. Formulas are included for the benefit of those who prefer to use the formula method. A complete list of formulas is given in Appendix A. The summaries are useful for emphasis and for review. The questions included are thought-provoking. They stress the many ways in which physics plays a part in the pupil's daily life, and they serve to test the ability of the pupil to apply physical principles. There are more mathematical problems than any one pupil is expected to solve. The grading of the problems makes it possible for the instructor to adapt the problems to groups of different ability. The average pupil should be able to solve all the problems in Group A. The problems in Group B are intended for the superior pupil, or they may be used for extra credit.

Newark, N. J. C. E. D.
June, 1939.

# *Acknowledgments*

SEVERAL PERSONS have assisted in various ways in the preparation of this book. The author takes pleasure in acknowledging their service, and in extending to each one his appreciation. Several of his colleagues in Newark have helped by offering valuable suggestions and in reading proof. The following teachers of physics in Newark have been particularly helpful: Mr. Roger Saylor of Barringer High School; Mr. Carl O. Voegelin of Central High School; and Mr. Carl Hunkins of Weequahic High School. Mr. Walter White, of Weequahic High School, offered valuable suggestions pertaining to the mathematical side of physics. Mr. Reyburn A. Higgins, Principal of West Side High School, read the galley proofs critically.

The photographs illustrating vibrations produced by the singing voice were taken by Dr. Dayton C. Miller, of the Case School of Applied Science, and the remarkable photographs of sound-waves were furnished by Professor Arthur L. Foley of Indiana University. The photographs of the Wright Brothers and of their first power-driven airplane were furnished by Mr. Orville Wright of Dayton, Ohio.

The author is grateful to Mr. John Mills for suggestions pertaining to the sections which deal with radio and for illustrative material which he supplied through the Bell Telephone Laboratories. The Aëronautical Society of Lansing, Michigan, kindly supplied material pertaining to the airplane.

Several friends and users of the former editions of this book have offered valuable suggestions for its improvement. Mr. Alton L. Hall of Pasadena, California, furnished the Hall Rule and offered constructive criticisms. Mr. Ernest A. Maynard, Jamaica High School, offered many helpful suggestions. Mr. Ralph H. White, of Camden High School, Camden, New Jersey, offered suggestions pertaining to the chapter on static electricity. Several suggestions were offered by Mr. H. M. Morley, of Los Angeles, California, and by Mr. William O Brooks, of Springfield, Massachusetts.

The author gratefully acknowledges the help which those named have given, but he completely exonerates all of them from any blame for imperfections which may be found in the book itself. For any errors he accepts full responsibility. The best photographic material and the most up-to-date information dealing with practical topics is in the hands of the manufacturers. They have been most co-operative in supplying information and photographic material. The author has in each case acknowledged the courtesy of the manufacturers supplying illustrative material directly below the illustration itself.

# Contents

## *Unit One*

## MATTER AND MECHANICS

CHAPTER PAGE
1. Matter and Its Properties . . . . . 3
2. Mechanics of Liquids . . . . . . 19
3. Mechanics of Gases . . . . . . 49

## *Unit Two*

## MOLECULAR PHYSICS

4. Molecules — Their Behavior . . . . 89

## *Unit Three*

## FORCE AND MOTION

5. Force . . . . . . . . . 109
6. Motion . . . . . . . . . 135

## *Unit Four*

## WORK — POWER — ENERGY

7. Work — Power — Energy . . . . 165

## *Unit Five*

## MACHINES

8. Machines . . . . . . . . 177

## *Unit Six*

## HEAT

9. Heat — Thermometry . . . . . . 205
10. Heat — Expansion . . . . . . . 215
11. Heat Units — Change of State . . . . 229
12. Heat — How It Is Distributed . . . . 254
13. Heat and Work . . . . . . . 270

## *Unit Seven*

## SOUND

CHAPTER PAGE
14. Sound . . . . . . . . 287
15. Sound — Music . . . . . . 304

## *Unit Eight*

## LIGHT

16. Light . . . . . . . . 323
17. Light — Reflection . . . . . . 337
18. Light — Refraction . . . . . . 350
19. Light — Optical Instruments . . . . 362
20. Light — Color . . . . . . . 386

## *Unit Nine*

## MAGNETISM AND STATIC ELECTRICITY

✓ 21. Magnetism. . . . . . . . . 403
✓ 22. Electricity — Static or Frictional . . . 415

## *Unit Ten*

## CURRENT ELECTRICITY

✓ 23. Current Electricity — Voltaic Cells . . . 433
✓ 24. Effects of the Electric Current . . . . 450
✓ 25. Measuring Instruments . . . . . . 481
✓ 26. Induced Currents . . . . . . . 496
✓ 27. Electro-Magnetic Induction . . . . . 515 503

## *Unit Eleven*

## RADIO AND RADIATIONS

✓ 28. X Rays — Radio — Radio-Activity . . . 531-537

## *Unit Twelve*

## TRANSPORTATION

29. The Automobile — The Airplane . . . 567
Appendix A: Formulas . . . . . . . i
Appendix B: Tables . . . . . . . iv
Index . . . . . . . . . . xi

# Unit One

# *Matter and Mechanics*

## Preview

PRIOR TO THE MIDDLE AGES LITTLE WAS KNOWN concerning the facts and principles of nature. The Romans were content to accept the ideas which they borrowed from the Greeks. Aristotle believed that all matter consists of four fundamental elements: earth, air, fire, and water. He was wrong in all four cases. He was wrong, too, when he believed that heavy objects fall several times as fast as light ones. But Aristotle was a philosopher, and he did little work in experimentation. The modern scientist may guess, but he immediately begins a series of experiments in an effort to learn whether his guess is correct.

Archimedes discovered an important principle of physics more than 200 years before the birth of Christ. He also learned something about the relation of mathematics to some simple machines, such as the lever and the pulley.

It seems highly probable that the Egyptians knew something about the use of an inclined plane. No one seems to know how they succeeded in getting the enormous blocks of stone into position in building the Great Pyramids. It is believed that they must have constructed some sort of ramp up which they could slide these stones to their positions.

You live in a scientific age in which progress is so rapid that no one can keep abreast of the various fields of science. It is most important for pupils to have some knowledge of the laws and principles of physics, because it is a basic science. Then you will have a foundation upon which to build. It is a great satisfaction to have a knowledge of one's environment. It is equally important to learn how men are succeeding in their efforts to control and improve their environment.

Through the importance of machines in World War II the study of physics has received a decided upsurge. It is significant that the United States Navy requires of its applicants a knowledge of physics for 26 out of 26 jobs in the Navy. Even in peacetime, our country needs a powerful Navy; we use automobiles and airplanes in peace as well as war; in the future we may even have airplanes driven by jet propulsion. Television will call for men trained in science, and no doubt radar will be used in many ways, particularly in locating objects and preventing collisions.

# *Matter and Its Properties*

## 1. Introduction

**1. Physics is a fundamental science.** Jules Verne dreamed of traveling beneath the sea. His dream has now become a reality. Darius Green dreamed of flying through the air. The China Clippers now make regular flights across the Pacific Ocean, and airplanes travel from Boston to Los Angeles at a speed which puts to shame the flights of Mercury, the messenger of the old Roman gods. Many of the dreams of yesterday have become the commonplaces of today. Man is indebted to the science of physics for much of the progress that one observes in this machine age.

With a "70-horsepower voice" we shout across the Atlantic Ocean. The man in New York talks to his neighbor in San Francisco. With our huge telescopes, we bring the heavenly bodies closer so that we can study them the better. We harness Niagara Falls or build the Grand Coulee dam to turn the energy of "white coal" into electrical energy. To accomplish such results, our engineers must have a knowledge of the science of physics.

Possibly you find many questions from day to day to which you would like an answer. "What makes the water flow out of the tap when the faucet is opened?" "How does electricity get to your home, and how does it produce heat and light, or turn an electric motor?" "What makes your automobile engine run?" "What causes the wind to blow?" "Why do you slip on wet pavements but not on dry ones?" "How does your clothing keep you warm?" "How does the sound get from your teacher's lips to your ear?" "How does the heat get from the furnace in the basement to the radiators in your schoolroom?" If you study physics, you will find the answers to such questions. It is the province of physics to answer the questions "Why?" "How?" and "What?" which are constantly arising.

**2. What is "science"?** The word itself comes to us from the Latin word *scientia*, which means *knowledge*. But our word "science" means more than knowledge. Science has been defined as *classified* knowledge. It is the work of the scientist to accumulate knowledge, to classify it, to card-index it so

---

### Vocabulary

MATTER, anything that takes up room.

ENERGY, capacity for doing work.

INERTIA, disinclination of matter to move or stop moving.

DENSITY, weight per unit volume.

FLYWHEEL, a heavy-rimmed wheel attached to the crankshaft of a gas engine or some other machine.

THEORY, an explanation of natural phenomena partially verified, but not usually capable of laboratory proof.

SCIENCE, classified knowledge.

FIG. 1. Physics is a science which deals with solids, liquids, and gases.

that it will be usable, to formulate certain laws and principles that pertain to it, and to compare the relationships of the various fields of knowledge.

Many persons find it difficult to give good definitions. Suppose we are asked to define the word "sled." In what class shall we put it? It is a vehicle. How does it differ from other vehicles? It has runners. Hence, a sled is a vehicle that has runners. Suppose we try to define botany. In what class do we find it? Botany is a science. How does it differ from other sciences? It deals with the study of plant life. Hence, we cannot be far wrong if we define botany as that science which deals with the study of plant life. You will find less trouble with your definitions if you make them try to answer the two questions: (*a*) To what class does it belong? (*b*) How does it differ from everything else in that class?

**3. What is this study which we call physics?** In which class of studies do we find it? It is a science. How does it differ from other sciences? It deals with matter and energy and also with physical changes in matter. It is true that such sciences as chemistry and geology also deal with matter and energy, but they do not deal particularly with the physical changes in matter.

There are five subdivisions or major units in physics: *mechanics*, *heat*, *sound*, *light*, and *electricity*. In this book they will be studied in the order just given.

**4. What is matter?** Since physics deals with matter, let us pause to inquire what we mean by matter. Wood, iron, copper, gold, and salt are all examples of matter. The liquids are also included; the gases, too, are examples of matter. *We may define matter as anything that takes up room or occupies space.* If we recall how a tire flattens after a puncture, it seems obvious that the escaping air must have taken up room in the tire.

**5. What is energy?** We did not include heat, light, and electricity among the examples of matter. They do not take up room, and we would find it difficult to weigh them. They are really forms of energy. *One usually defines energy as the ability to do work.* Man puts heat energy to work in a steam engine. In many cases we call upon electrical energy to do our work for us. The photographer uses light energy when he exposes a film or plate.

**6. What is the structure of matter?** Theoretically, a piece of marble may be broken into two pieces, those two into four, and so on to infinity. In reality, no kind of matter can be subdivided beyond a certain point without losing its identity. Water may be split up into two gases, but when this happens it loses its characteristic properties. The smallest particle into which matter can be subdivided without destroying its *characteristic* properties is called a *molecule.*

No one has ever seen a molecule; these particles are so small that the best microscope fails to reveal them. Suppose that a drop of water were magnified until its diameter equaled that of the earth; if its molecules at the same time were correspondingly increased, it is estimated that they would appear about the size of baseballs. By indirect methods it has been learned that one liter (a trifle more than a liquid quart) of air contains $27 \times 10^{21}$ molecules. If the student will write the figure 27 followed by 21 ciphers, he may have a better concept of the minute size of these particles. An adult in deep breathing may inhale about four times that number of molecules at a single inhalation.

As we inflate an automobile tire to a pressure of 30 lb. per sq. in., we are merely pumping more air molecules into the tire. It is possible to pump into such a tire two times as many molecules as it had contained, three times as many, ten times as many, or even more than that if the tire is strong enough so that it will not burst under the increased pressure. We are crowding the molecules together more closely, or reducing the distances between them. Despite the enormous number of molecules present in such a tire, we must conclude, as we crowd so many more into the same space, that they could not have been even relatively near neighbors.

The tiny molecules are made up of even smaller particles called *atoms.* We may change matter in any way we see fit, but if we do not break up the molecule, we have a *physical change.* In the science of physics, *the molecule is the unit of matter.*

If we break matter up into its atoms, we have a *chemical change. The chemist's unit of matter is the atom.* In the laboratory, the chemist builds up new molecules from atoms, he breaks up complex molecules into atoms, or he rearranges the atoms in the molecule. By the use of the X rays, scientists have learned how the atoms are arranged in certain molecules. For example, a molecule of table salt has the latticed structure shown in Fig. 2. The black and the white particles represent atoms of sodium and chlorine, of which the salt is composed.

Until about the beginning of the

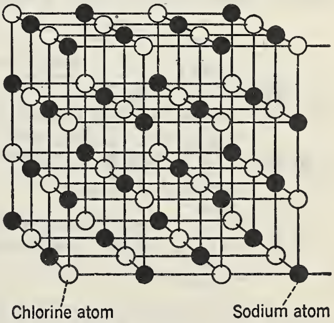


FIG. 2. Common table salt is composed of sodium and chlorine atoms.

twentieth century, scientists believed that the atom could not be subdivided and that it was homogeneous throughout. The discovery of the X ray and the isolation of radium forced us to change our views. Chemists and physicists are certain that the various kinds of atoms are complex structures. We picture the modern atom as having a *nucleus* made up of electrically charged particles. Those electrically charged particles which have a *positive*, or plus, charge are called *protons*. Every proton has almost the same weight as that of the hydrogen atom. There are also some particles in the nucleus of the atom that do not carry an electrical charge. They are called *neutrons*. Surrounding the nucleus, and probably revolving around it in much the same manner that the earth and the other planets revolve around the sun, there are some extremely minute particles known as *electrons*. (See Fig. 3.) Each electron carries a charge of *negative* electricity. The hydrogen atom is the lightest atom known, but it is 1840 times as heavy as an electron.

**7. There are three states of matter.** Everyone knows that matter can exist in three states: *solids*, *liquids*, and *gases*. Solids have a definite volume and a definite shape; liquids have a definite volume, but they take the shape of the containing vessel; gases have neither a definite volume nor a definite shape. Gases not only take the shape of the containing vessel, but they expand and fill the vessel, no matter what its volume. In solids, the molecules cling quite firmly together and do not change their relative positions readily; hence solids have a definite shape. In liquids, the attraction between the molecules is less, and they slide over one another quite readily. For this reason, liquids change their shape unless they have lateral support. In gases, the molecules move so freely that they tend to separate; hence the indefinite expansion.

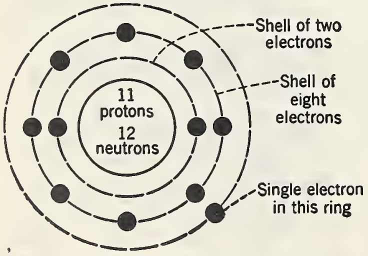


Fig. 3. The sodium atom has 11 electrons in rings or circles of 2, 8, and 1. It has 11 protons and 12 neutrons.

It is rather difficult to classify a substance like sealing wax, which breaks when struck a sharp blow, but flows under pressure. Both liquids and gases flow freely; hence both are called *fluids*, from the Latin word *fluere*, which means *to flow*. A liquid that flows easily is said to be *mobile;* such a substance as tar, which flows slowly, is said to be *viscous*.

Since heat causes the molecules to move more rapidly, an increase in temperature promotes fluidity. Motor oils that are quite viscous in cold weather become quite mobile in summer. In fact, an increase in temperature may convert a solid first into a liquid, and then into a gas or vapor. Water readily changes to ice, a brittle solid, if cooled to 32° F.; when its temperature is increased to 212° F., water is converted into steam, which is a gas or vapor. Even such a solid as iron can be melted or even changed to a gas by heating it to a very high temperature.

**8. Changes take place in matter.** Many changes are constantly taking place in matter. Wood burns; water freezes; salt dissolves in water; milk sours. These are merely examples of hundreds of changes occurring daily. Changes in matter are of two kinds, *physical* and *chemical*. If the identity of a substance is not lost, the change is *physical;* if a new substance with new characteristic properties is formed, the change is *chemical*. When milk sours, it loses the characteristic properties of sweet milk. Such a change is chemical. The burning of wood is also a chemical change. When water freezes, its molecules are not broken up or rearranged. An increase in temperature converts it to its former state. Such a change is physical. *Physics* deals with *physical* changes in matter; *chemistry* deals with *chemical* changes.

**9. Matter is indestructible.** If we weigh a block of ice, melt it, and weigh the water which is formed, we find that there is no change in weight. *No matter has been lost.* The chemist may let a piece of iron rust, and then recover the iron from the rust. It will have the same weight as the original piece of iron. We may change the form of matter or change its state, but we cannot destroy it. While we cannot destroy matter by means of either a physical or a chemical change, neither can we create matter. Hence the total quantity of matter in the universe is the same today as yesterday. The fact that matter cannot be created or destroyed is usually called the *law of the conservation of matter.*

**10. Matter has properties.** Steel is hard; hence it makes good cutting tools. Aluminum transmits heat readily; hence it is suitable for cooking utensils. Different substances have different properties. Some properties, weight and volume, for example, are common to all substances. They are spoken of as *general* properties. There are also many *special* properties which are common to certain substances only. We identify substances by studying their special properties. The use to which a substance is put depends upon its special properties. Since steel is hard and can be tempered, while tin is soft, we make knife blades of steel instead of tin. We use diamonds to cut extremely hard rock.

## 2. General Properties of Matter

**11. What is volume?** If matter occupies space, it must have length, breadth, and thickness. In other words, matter has *volume*. When we studied arithmetic, we learned how to find the volume of rectangular solids *directly* by obtaining the product of their length, breadth, and thickness. By the use of an *indirect* method in the laboratory, we shall learn how to find the volume of any solid, no matter how irregular it may be. Liquids and gases also occupy space and have the property of *extension*, or volume.

**12. What is meant by mass?** Suppose that we have a certain object. It contains a definite quantity of matter. *The measure of the quantity of matter which a body contains is called its mass.* The mass of a body does not vary. We may squeeze a body and reduce its volume, but the quantity of matter in it remains the same. We may take the body up on a high mountain, or even to the moon or the sun, but its mass will remain constant.

**13. What is weight?** If we release a ball, it falls to the ground. We say that it is attracted to the earth by the force of gravity. When we find the weight of an object, we are merely measuring the attraction of the earth for that body. The weight of an object depends upon two things: (*a*) the mass or quantity of matter that it contains; (*b*) the measure of the earth's attraction for it. The first does not vary, for an iron ball will contain the same quantity of matter at *any* place, either at the surface of the earth or 100 miles from the surface. But the second factor does vary, for the earth's attraction for a body will be less upon a mountain than in a valley, and an object will weigh less 100 miles above the surface of the earth than it does at the surface. *Weight is defined as the measure of the earth's attraction for a body.*

**14. Impenetrability is a general property.** One car must give way to another at a street intersection. Both cars cannot cross at once or be in the same spot at the same time. We cannot pour water into a bottle through a narrow opening unless we make some provision for the air inside the bottle to escape. The air takes up room. A nail driven into a board does not penetrate the wood, but it pushes the fibers of the wood aside. From such examples, we must conclude that *no two objects can occupy the same place at the same time,* because *matter is impenetrable.*

We can make use of the property of *impenetrability* to find the volume of an *irregular* solid. We put into a graduated cylinder enough water to cover the irregular object and note the mark to which the water rises, as in Fig. 4. As we then lower the solid into the water, the displaced water will rise to a higher level. The difference between the two graduation marks equals the volume of the water displaced. The volume of the water displaced just equals the volume of the irregular solid. We can find the volume of any insoluble, non-porous solid by this method.

**15. What is porosity?** All matter is more or less porous. The large pores of the sponge cannot escape detection. The pores of an unglazed brick are not so obvious, but water readily finds its way through the brick. Cistern water is often filtered through brick. Iron and silver have still smaller pores, but water under enormous pressure can be forced through even these. When given quantities of alcohol and water are shaken together the combined volume decreases slightly, due to the porous nature of these liquids. Some of the alcohol molecules occupy the spaces between the water molecules, and *vice versa.*

**16. What is meant by inertia?** You board a car or a bus, find the seats all occupied, and grab a strap for support. When the car starts forward suddenly, you are jerked backward. Your body was at rest while the car was standing

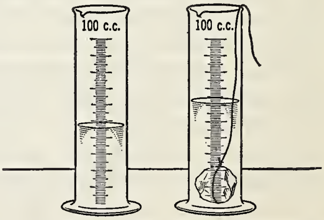


FIG. 4. Because the solid is impenetrable, it displaces its own volume of water.

*Courtesy of the Pennsylvania Railroad*

Fig. 5. Because water has inertia, it can be scooped up by the train as it travels at high speed.

still, and a body at rest has a tendency to remain at rest. Your body was *inert*, or *inactive*, and the car seemed to be trying to go forward and leave you at rest. If the car stops suddenly, you lurch forward. Your body was in motion with the car, and, when the car stops, your body tends to keep on moving. Matter has no ability in itself to move or to stop moving. Matter is *inert*, which means that it is inactive or lazy. Since all matter has the property of inertia, *bodies in motion tend to remain in motion and bodies at rest tend to remain at rest.* It requires some force, such as a push or a pull, to overcome the inertia of a body and set it in motion or stop it when it is in motion.

There are many examples of inertia. A car going 40 miles per hour strikes a tree. The driver is likely to continue on forward and be thrown through the windshield. If one leaps from a rapidly moving car, he is likely to fall in the direction in which the car was moving, because inertia pushes his body forward, while his feet are stopped by the friction of the pavement.

Sometimes inertia is put to *practical use*. We stand in front of a furnace with a shovelful of coal. As we swing the shovel and coal forward toward the furnace door, both the shovel and the coal are in motion. Then we stop the shovel, but, on account of its inertia, the coal continues on into the furnace. In running a sewing machine, the operator pushes downward first with the toe and then with the heel. The rim of the band wheel has enough inertia to keep the machine in smooth, steady operation between such successive pushes. The flywheel on the crankshaft of a gasoline engine has a heavy rim to supply the inertia needed to keep the engine running smoothly, although the explosions which drive the engine are intermittent and not continuous.

The shallow metal trough shown in Fig. 5 is used to supply water to a rapidly moving train. When the fireman lowers a metal scoop into the trough, the inertia of the water forces

*Courtesy of the Port of New York Authority*

FIG. 6. With its approaches, the George Washington Bridge is 8700 feet in length. The steel cables, which are 36 inches in diameter, support the weight of the bridge.

it up into the tender. A college boy trying to save railroad fare by riding beneath the tender was most emphatic in his statement that this method works, even at two o'clock in the morning.

## 3. Some Special Properties of Matter

**17. What is tenacity?** By laboratory test we find that a silk thread is stronger than one of cotton, if both have the same diameter, or the same cross-sectional area. A copper wire is more easily broken than one of steel. We say that steel is more *tenacious* than copper. When we ride in an elevator, our safety depends upon the *tenacity* of the cable. The tenacity of any material, or its *tensile strength*, is measured by the force needed to break a rod or wire of that material whose cross-sectional area is unity, one square inch for example. (See Table 7, Appendix B.) It takes a load of 300,000 lb. to break a bar of high-grade steel whose cross-sectional area is one square inch. (See Fig. 6.)

The steel cables that sustain the weight of the George Washington Bridge are 36 inches in diameter. A single span of the Golden Gate Bridge of San Francisco stretches over 4200 feet of water. (See Fig. 7.)

Increasing the temperature of a metal weakens its tensile strength. Metals suffer from *fatigue*, too. If a

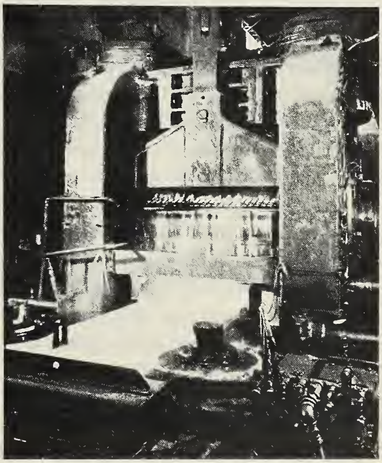
*Courtesy of the Redwood Empire Association*

FIG. 7. This bridge spans the famous Golden Gate at a height of 250 feet above the water. The center span, which is about 4200 feet in length, is supported by cables of 25,000 strands each. The towers from which the cables are suspended rise above the water to a height almost equal to that of the Woolworth Building.

load is held by a cable for a long time, the cable may eventually break under the load which it held safely at first.

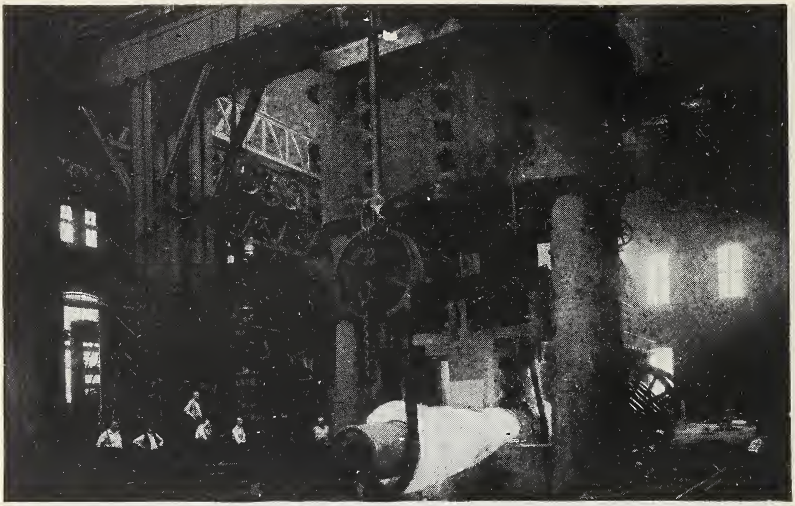
**18. What is ductility?** (*Ducere* means *to lead.*) One end of a copper rod is pointed so that it will pass through a tapering hole in a steel plate or a die. The small end is then fastened to a wheel which, as it turns, pulls or draws the rod through the opening. Thus its diameter is reduced and its length increased. A metal that can be drawn into wire in such a manner is said to be *ductile*. Gold, silver, platinum, and iron are examples of other ductile metals.

Wires of very small diameter are often made by drawing the metal through a tiny hole drilled in a chip diamond. Such diamond dies are used for making the extremely fine filaments for use in electric light bulbs. The metal used is tungsten, and it can be drawn to a diameter which is less than one-sixth that of an average human hair. Platinum, the most ductile of the



*Courtesy of the United States Steel Corporation*

FIG. 8. The white-hot steel passes through huge rolls which squeeze the bar, reducing its thickness and increasing its length.



*Courtesy of the Bethlehem Steel Company*

FIG. 9. Steel is heat-treated by hammering it, rolling it, or pressing it between the piston and frame of the hydraulic press. Some large presses exert a force as great as 14,000 tons.

metals, has been drawn into wires only 0.00003 inch in diameter. At high temperatures glass is very ductile. Quartz has been spun into threads so fine that it is impossible to see them with the naked eye.

**19. What is malleability?** Iron, copper, lead, aluminum, platinum, and gold may be hammered or rolled into sheets. (See Fig. 8.) Such metals are said to be *malleable*. Gold is so very malleable that it has been beaten into sheets so thin that it would take 250,000 to make a pile one inch high. It would require about 1000 such sheets to equal in thickness a single leaf of this book. Such thin sheets of metal are translucent; that is, they transmit some light through them. Fig. 9 shows a forge for working hot steel. Some large presses for making armor plate exert a force of 14,000 tons.

**20. What is hardness?** The diamond may be used to cut or scratch glass. Steel will cut tin or copper. We call a substance *hard* if it cannot be easily scratched or abraded. The term *hard* is only a relative one. For example, glass is harder than wood, but it is easily scratched by a diamond. Soapstone, or steatite, is so soft it may be easily scratched with the thumb-nail; it is often pulverized for use in talcum powder. When two substances of unequal hardness are rubbed together, the harder always wears away the softer the more rapidly, unless the soft substance is driven at a high velocity. Hard substances, like sand, emery, corundum, and diamond dust, are used extensively for cutting, grinding, and polishing.

**21. What is brittleness?** Glass and porcelain break easily when struck a sharp blow. A substance that is easily broken is said to be *brittle*. Students sometimes confuse hardness and brittleness. Glass is hard and brittle, but steel and some other substances may be hard and tough. Steel is *tempered* to give it the proper degree of hardness; its toughness is increased by heating it and then cooling it slowly. Glassware is cooled slowly to make it less brittle. The process is called *annealing.*

## 4. Measurement

**22. There are different systems of weight and measurement.** From earliest times, systems have been in use for weighing objects and for measuring them. The scientist in the United States and in England uses two different systems:

1. *The English system.* No doubt you are more or less familiar with this system. You know the number of inches in one foot, the number of feet in one yard, the number of ounces in one pound, and the number of quarts in one gallon. It is quite probable, however, that you may have forgotten the number of square yards in a square rod, or the number of cubic inches in one gallon. Some figures which you may need to use are given in Appendix B.

2. *The metric system.* This system originated in France at the time of the French Revolution. It is a decimal system similar to the table for United States money. If the cumbersome English system were abolished, any average pupil could learn the metric system in one lesson, because there are only three words and a half dozen prefixes necessary. The *meter* is the unit of *length;* the *liter* is the unit of *capacity;* and the *gram* is the unit of *weight.* The subdivisions of each of these units come from the Latin prefixes: *milli,* 1/1000; *centi,* 1/100; and *deci,* 1/10. Observe that these differ little from the mill, cent, and dime used in our monetary table. The multiples for each of the units in the metric system come from the Greek prefixes: *deka* or *deca,* 10; *hekto* or *hecto,* 100; and *kilo,* 1000. The metric system is used more or less exclusively in all civilized countries except Great Britain and the United States, and it is used by scientists in these countries.

**23. The metric tables.** *Lengths, areas, and volumes.* All of the units of the metric system are based upon natural standards. The meter was intended to be exactly 1/10,000,000 of the distance from the earth's equator to either pole. Because of a slight error, it equals that distance only approximately. By definition, the *standard meter* equals the distance, measured at 0° C., between two parallel lines scratched on a platinum-iridium bar kept at the International Bureau of Weights and Measures at Sèvres near Paris. From this standard, thousands of copies have been made. Our standard meter bar is kept at the Bureau of Standards in Washington, D. C. The pupil in his study of physics will find the following table useful:

10 *milli*meters (mm.) make 1 *centi*meter
10 *centi*meters (cm.) make 1 *deci*meter
10 *deci*meters (dm.) make 1 meter (m.)

He will also need to know that there are 1000 meters in one *kilo*meter.

Since we have two systems, it is desirable to know the values of the metric units when compared to the Eng-

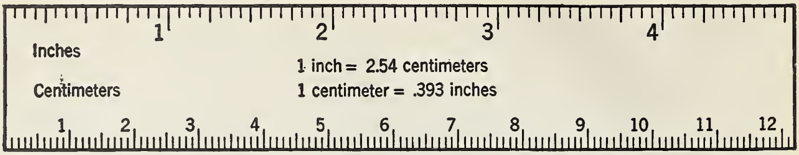


FIG. 10. The centimeter is nearly 0.4 of an inch in length. One inch equals 2.54 centimeters.

lish. *The meter equals 39.37 inches;* the yard equals $\frac{3600}{3937}$ of a meter. *One inch equals 2.54 cm.* One centimeter is approximately 0.4 of an inch. It is a small unit. (See Fig. 10.)

For measuring areas or surfaces, the *square meter* or the *square centimeter* is generally used. A floor 3 meters long and 2 meters wide has an area of 6 square meters. (See Fig. 11.) For measuring volumes, the *cubic meter* is used. A box 2 meters long, 1 meter wide, and 1.5 meters deep has a volume of 3 cubic meters. Vessels used for measuring liquids are often graduated in cubic centimeters (c.c.). The abbreviation cm.$^3$ is often used instead of c.c. Fig. 12 shows the relative sizes of one c.c. and one cu. in.

*Capacity.* If we construct a cubical box whose inside dimensions are 10 cm. on each side, that box will hold exactly one *liter*. In the United States, we use a *dry* quart measure for measuring berries and vegetables, and a *liquid* quart for measuring milk or gasoline. The dry quart is about 10 cu. in. bigger than the liquid quart. The liter is used for measuring either liquids or solids; it is smaller than our dry quart, but a little larger than our liquid quart. *The liter is equivalent to 1000 c.c., or to 1 cu. dm.* The same prefixes that are used in the table for lengths are used in the table for capacities in the metric system. (See Fig. 13.)

*Weight.* The cubical box mentioned in the preceding paragraph will hold exactly *one kilogram* of distilled water measured at a temperature of 4° C. From such knowledge we could construct a set of metric weights. One liter of water, or 1000 c.c., weighs one kilogram. Therefore, *one cubic centimeter of water weighs one gram.* Both the gram and the kilogram may be used as standards of weight in the metric system. Here, too, in the table of weights the prefixes *milli, centi, deci,* etc. are used. The metric ton (M.T.) is sometimes used; it is equal to 1000 kilograms.

The gram is a very small unit. A new five-cent piece weighs almost exactly 5 grams. The kilogram (kgm.) equals 2.2046 lb. Fig. 14 shows the relative sizes of the pound weight and the kilogram weight. (See Fig. 15).

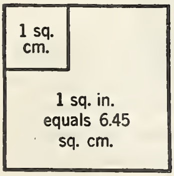


FIG. 11. Comparison of the metric and English units of area.

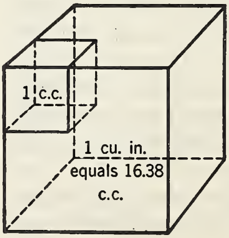


FIG. 12. The cubic inch contains more than 16 cubic centimeters.

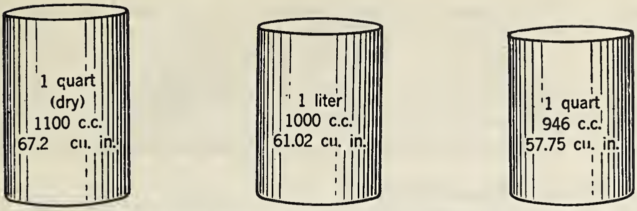


FIG. 13. Our *dry* quart measure is larger than the liter, but our *liquid* quart is slightly smaller.

**24. How do we measure time?** In both systems of measurement, the *second* is the unit of time. The metric system is often called the *centimeter-gram-second* (C.G.S.) system of measurement. The English system is known as the *foot-pound-second* (F.P.S.) system.

## 5. Density

**25. What is meant by density?** Sometimes we hear one say that lead is heavy or that cork is light. Such a statement means little. A cubic *foot* of cork is heavier than a cubic *inch* of lead. Of course one cubic inch of lead is heavier than one cubic inch of cork. If we wish to be exact, we may say that lead is *denser* than cork. Suppose we have certain blocks containing exactly one cubic foot of each of the following: lead, iron, wood, cork, and less-known balsa. When each one is weighed, we find the weights of *equal volumes* decidedly different. *The weight of a unit volume of a substance is called its density.* Of course we could have found the weights of one cubic inch of each substance or of one cubic centimeter. The unit volume selected for use in the English system is *one cubic foot.* In the metric system it is *one cubic centimeter.* Hence, density is expressed in *lb. per cu. ft.*, or in *gm. per c.c.*

To find the density of any substance we first weigh it. Then we find its vol-

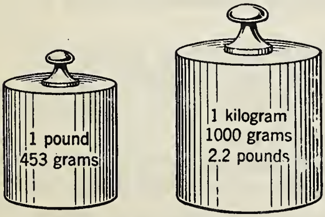


FIG. 14. The kilogram is more than twice as heavy as the avoirdupois pound.

*Courtesy of the National Bureau of Standards*

FIG. 15. The standard kilogram is almost indestructible. It is kept at the Bureau of Standards in Washington, D.C.

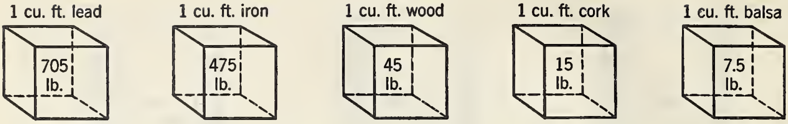


FIG. 16. Different substances have different densities, or different weights per unit volume.

ume, either by direct measurement or by the *indirect* method described in Section 14. Next, we divide its weight by its volume to find the weight of unit volume.

*Example.* A block of wood weighs 180 gm. It is 10 cm. long, 6 cm. wide, and 4 cm. thick. Its volume is 240 c.c. (10 cm. × 6 cm. × 4 cm.). If 240 c.c. of wood weigh 180 gm., then 1 c.c. weighs $\frac{180}{240}$ gm., or 0.75 gm. Therefore, the density of the block is 0.75 gm. per c.c.

We may derive a formula for use in solving problems involving density. The letter $D$ represents the density, the letter $W$ represents the weight, and the letter $V$ the volume. Then we have the formula,

$$D = \frac{W}{V}, \text{ or } DV = W.$$

Many times we shall have occasion to make use of the density of water. *It has been found to be 62.4 lb. per cu. ft. in the English system*, sometimes written 62.4 lb./cu. ft. *In the metric system the density of water is one gram per cubic centimeter*, or 1 gm./c.c.

These numbers should be memorized by the student.

PROBLEM. A gold brick is 15 cm. long, 10 cm. wide, and 5 cm. thick. If gold has a density of 19.3 gm./c.c., calculate the weight of the brick.

*Solution.* The volume is equal to the product of the length, breadth, and thickness. In this case it is 750 c.c. Since weight equals density times volume, then 750 × 19.3 gm. = 14,475 gm., the weight.

## Summary

Physics is a science which treats of matter and energy. It deals with *physical changes* in matter.

Matter is made up of very small particles called molecules. The molecule, which is the unit in physical changes, is made up of atoms. The atoms in turn contain still smaller particles called protons and electrons. The molecules of matter are always in motion. An increase in temperature increases molecular motion.

As the result of a physical change a substance does not lose its characteristic properties; a chemical change causes a substance to lose its identity.

Matter exists in three states: solids, liquids, and gases. Solids have a definite volume and a definite shape; liquids have a definite volume, but they take the shape of their container; gases have neither a definite volume nor a definite shape.

Certain properties, such as inertia, impenetrability, extension, weight, and indestructibility are common to all matter. Such special properties as ductility, malleability, tenacity, hardness, and brittleness are peculiar to certain substances.

The student should memorize the following metric-English equivalents: 1 m. equals 39.37 in.; 1 in. equals 2.54 cm.; 1 kgm. equals 2.2 lb. Other equivalents are given in Appendix B.

The density of a substance is the weight of a unit volume of that substance. The student should remember that 1 c.c. of water weighs 1 gm.; also that 1 cu. ft. of water weighs 62.4 lb. For solving problems, the following formula is useful:

$$D = \frac{W}{V}.$$

*How many of the following terms can you define or explain? (Try first; then check your answers.)*

Matter
Energy
Molecule
Atom
Homogeneous
Nucleus
Proton
Electron
Solids, liquids, and gases
Fluid
Conservation of matter

Volume
Mass
Weight
Gram
Liter
Gravity
Mobile
Viscous
Impenetrability
Porosity
Physical change

Inertia
Tenacity
Ductility
Tensile strength
Malleability
Hardness
Brittleness
Anneal
Meter
Density
Chemical change

## QUESTIONS

1. Name three physical changes and three chemical changes.

2. Could you find the volume of a lump of sugar by using the indirect method described in Section 14? Explain.

3. What two difficulties would you encounter in trying to find the volume of a piece of cork by the method described in Section 14?

4. Is it correct to say that wood can be destroyed by burning it? Explain.

5. Is it an exception to the general property of impenetrability when we drive a nail into a board or push a needle through a piece of cloth? Explain.

6. Sometimes water pipes jar or vibrate when the water is turned off suddenly. Explain.

7. How is the principle of inertia utilized in beating or shaking a rug or carpet?

8. How do we make use of inertia in shoveling coal or snow?

9. Mention two practical applications of inertia. Mention two examples of the property of inertia that are of no practical value.

10. Explain why shaking or jarring a tree will bring down apples, nuts, etc.

11. Why does a heavy flywheel cause machinery to run smoothly?

12. Why does it require more force to start a car than it does to keep it moving?

13. Give reasons why it is illegal to park motor trucks on bridges.

14. Why should one face forward when alighting from a car or bus?

15. How does heating a steel cable affect its tensile strength or its tenacity?

16. In Fig. 17 the segment of string supporting the ball is cut from the same piece as the segment attached below the ball.

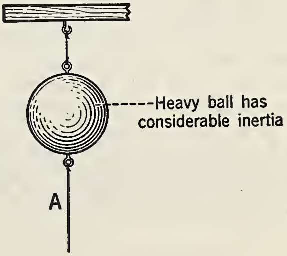


FIG. 17. The heavy ball has considerable inertia.

If one pulls with a quick jerk at $A$ the string will break below the weight. If one pulls steadily at $A$, the string will break above the weight. Explain.

17. What advantages has the metric system of weights and measures over the English system?

18. Why is it more exact to say that lead is "dense" than to say that lead is "heavy"?

## PROBLEMS

*(Refer to Tables 1 and 2 in Appendix B.)*

### GROUP A

1. Calculate the value of 1 ft. in cm.; of 1 oz. in gm.

2. Calculate your height in meters; your weight in kilograms.

3. The Empire State Building is 1248 ft. high. What is its height in meters?

4. A train runs the 960 miles from New York to Chicago in 18 hours? What is its average speed in miles per hour?

5. A train runs at the speed of 100 kilometers per hour? What is its speed in meters per second?

6. In his flight to Paris, Lindbergh flew 3610 miles at an average speed of about 100 miles per hour. Calculate the distance of his flight in kilometers, and his speed in kilometers per hour.

7. With its approaches, the San Francisco-Oakland Bridge is 8.5 miles long. What is its length in kilometers?

8. A tank is 6 ft. long, 4 ft. wide, and 5 ft. deep. How many pounds of water can it hold?

9. Stone has a density of 150 lb. per cu. ft. Calculate the weight of one cubic yard of stone.

10. A manufacturer wishes to make a 1000-gm. brass weight. How many c.c. of brass, density 8.4 gm. per c.c., will be needed?

11. Calculate the number of grams in one ounce. How many centimeters are there in one yard? How many kilometers are there in one mile?

### GROUP B

12. Gold is 19.3 times as dense as water. Calculate the weight of a gold brick 8 in. long, 4 in. wide, and 2 in. thick. This is about the size of an ordinary brick. How do the weights compare?

13. How much heavier is a pound of feathers than a pound of gold? How much heavier is an ounce of gold than an ounce of feathers?

14. A grocer buys a bushel of berries. He measures them out to his customers with a liquid quart measure. How many quarts does he get?

15. A 12-lb. shot is to be made of lead. Lead has a density of 705 lb. per cu. ft. How many cu. in. of lead are needed?

16. A rod 10 ft. long has a diameter of 2 mm. It is drawn through a die which reduces its diameter to 1 millimeter. How do the cross-sectional area and the length of the new rod compare with those of the original rod? Is its mass changed?

17. An ice box is 18 in. long, 12 in. wide, and 10 in. deep. If ice is 0.92 times as dense as water, how many pounds of ice will the box hold?

18. A copper rod is 5 cm. in diameter and 200 cm. long. If copper has a density of 8.8 gm. per c.c., calculate the weight of the rod in grams. In kilograms.

19. A man has a tube of small diameter. He places some mercury in the tube, measures the length of the mercury column, and then weighs the mercury. If the mercury column is 400 mm. long, and its weight is 0.533 gm., what is the diameter of the tube? Density of mercury is 13.6 gm. per c.c. (Hint: Find the volume of mercury from weight and density. Then find the diameter of a cylinder, having volume and length given.) What do you think is the chief objection to this method?

# *Mechanics of Liquids*

## 1. Liquid Pressure and Total Force

**26. What are force and pressure?** If we push against a wall, we are using force. If we pull upon an automobile, we are using force. *We may define force as a push or a pull.* Force is generally measured in grams or in pounds. In our study of physics we shall use the term "pressure" to indicate the force which is applied to *unit area.* For that reason, we measure pressure in *lb. per sq. in.*, or in *gm. per sq. cm.* Total force is measured in pounds or grams, since it applies to the force acting against the total area of some particular surface.

**27. Do liquids exert pressure?** Suppose we have a large wooden tank filled with water or some other liquid. If we bore a hole in the bottom of the tank, the liquid will flow out, thus proving that liquids push *downward* upon the bottoms of their containers. This is what one might expect, since liquids have weight. If we bore a hole in one side of the tank, the liquid will flow out through this opening, proving that liquids exert pressure in a *sidewise* direction, too. If we push a piece of wood down into a vessel of water, it will rise to the surface of the water again as soon as it is released. One must use force to *hold* a block of wood beneath the surface of the water. Evidently the water must exert an *upward* push upon the block of wood. The upward push which liquids exert upon objects submerged in them causes some objects to lose all their apparent weight and float, and it causes dense objects to lose part of their weight. Therefore, we conclude that liquids exert pressure in all directions, *downward*, *sidewise*, and *upward.*

**28. Liquid pressure is proportional to the depth.** Just as a brick lying on a table presses upon the table, so water or any other liquid poured into a vessel exerts force or pressure upon the bottom of the vessel. Such force is due to the weight of the liquid. When several bricks are piled upon one another, the downward pressure is increased. Likewise, every layer of liquid sustains the weight of the layer directly above it; hence the *pressure of a liquid must increase in direct proportion to the*

---

### Vocabulary

CALIBRATE, to graduate an instrument, or to verify its graduation.

CYLINDER, a tubular chamber in an engine or other machine.

PISTON, a solid cylinder that fits the tubular chamber of an engine, or other machine, gastight; but it may be driven back and forth by gas, steam, or other pressure.

HYDRAULIC, pertaining to liquids in motion.

HYDROSTATIC, pertaining to liquids at rest.

LAW, a statement of natural processes and phenomena; it is generally capable of laboratory proof.

MANOMETER, a pressure gauge or vacuum gauge.

PRESSURE, force acting on unit area.

*depth.* If the unit area pressed upon is 1 sq. cm., as in Fig. 18, then water 1 cm. deep exerts a pressure of 1 gm., which is the weight of 1 c.c. of water; the pressure at a depth of 2 cm. equals 2 gm.; for each cm. increase in depth the increase in pressure is 1 gm. If the unit area pressed upon is 1 sq. ft., water 1 foot deep exerts a pressure of 62.4 lb. This is also the weight of 1 cu. ft. of water. The student must picture in his imagination that 1 cu. ft. of water 1 foot deep rests upon a base having an area of 1 sq. ft. On each sq. in., the pressure of water is $\frac{1}{144}$ of 62.4 lb., or *0.433 lb. for each foot in depth.*

**29. Liquid pressure is proportional to density.** Liquids vary in density. Mercury is a dense liquid, weighing 13.6 times as much as an equal volume of water. Since the pressure caused by liquids is due to the weight of the liquid, we would expect mercury to exert much greater pressure than water of the same depth. Experiment shows that our reasoning is correct. *The pressure exerted by a liquid is directly proportional to its density.* We have learned that water 10 cm. deep exerts a pressure of 10 gm. Mercury 10 cm. deep exerts a pressure of 136 gm. (10 × 13.6 gm.). Since gasoline is only about 0.7 as dense as water, the pressure exerted at a depth of 10 cm. in gasoline is only 7 gm. (10 × 0.7 gm.). Put in the form of an equation,

$$\textit{pressure} = \textit{depth} \times \textit{density}.$$

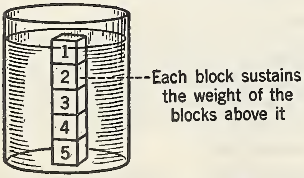


FIG. 18. Liquid pressure increases with the depth of the liquid.

Using the letter $p$ to represent pressure, $h$ for depth, and $d$ for density, the equation becomes

$$p = hd.$$

PROBLEM. A diver goes down to a depth of 150 ft. in sea water; density equals 64 lb./cu. ft. Calculate the pressure on each sq. ft. of his body. Calculate the pressure on each sq. in. of his body.

*Solution.* The depth $h$ is given as 150 ft.; and the density $d$ is 64 lb./cu. ft. The pressure $p$ is required. Substituting these values in the formula, $p = hd$, then $p = 150 \times 64$, or 9600 lb. on each sq. ft. To find the pressure in pounds per sq. in., we divide 9600 lb. by 144, the number of sq. in. in 1 sq. ft. The quotient is 66.7 lb.

PROBLEM. For fighting fire in a certain city, water must be supplied at a pressure of 150 lb. per sq. in. How high must a reservoir be above the city to supply such pressure?

*Solution.* $p = 150$ lb. per sq. in.; $d = 62.4$ lb./cu. ft.; $h$ is unknown. From the equation,
$p$ (in lb. per sq. in.) = $\frac{h \text{ (in ft.)} \times d \text{ (in lb. per cu. ft.)}}{144}$. Substituting, $150 = \frac{h \times 62.4}{144}$.

Then, $150 \times 144 = h \times 62.4$. Whence, $h = 346.1$ ft.

**30. How is liquid pressure affected by direction?** A pile of bricks resting on a table exerts pressure in a *downward* direction only, because the bricks are solid and their molecules do not move over one another freely. The molecules of a liquid, however, move over one another so freely that a liquid takes the shape of its container; therefore we may expect liquids to press outward in a *sidewise* direction. Our study of floating objects convinces us that liquids push *upward* toward the surface as well as *downward* and *sidewise.*

To illustrate, we may pour mercury

into the three tubes shown in Fig. 19 until it stands at the same height in each, and then lower them all into water so that the open ends are at the same depth. The pressure of the water will cause the mercury to rise in the long arm of each tube. At *A* the water presses *downward;* at *B* the pressure is *upward;* while at *C* a *sidewise* pressure is exerted. The mercury stands at the same level in the long arm of each tube. As measured by the mercury columns the pressures are all equal. This is one way of showing that *liquid pressure is independent of direction.*

Let us try to picture a drop of water in the center of a glass of water. The pressure upon this drop of water must be *equal in all directions*, or currents would be produced in the water.

**31. How does the shape or area of the container affect liquid pressure?** Since pressure is measured in terms of unit area, such as lb. per sq. in., or gm. per sq. cm., we need not consider the *total* area in solving problems dealing with liquid pressure. The area of the liquid surface inside a teakettle is much greater than that of the liquid in the spout, but the pressure is the same in both cases. If the pressure increased with the area, water would always flow out of the spout of the teakettle.

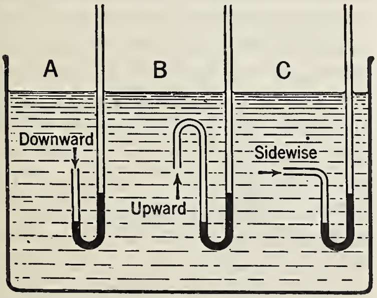


Fig. 19. Liquid pressure does not depend upon the direction.

From the preceding section, one would infer that liquid pressure is independent of the *shape* of the container. Pascal's vases may be used to demonstrate this fact. (See Fig. 20.) The area of the diaphragm at the bottom of these vases is the same, and it may be considered as unity. A pointer used to show the increase in pressure as water is poured into these vases indicates the same pressure for all three vases, although their shapes are different and the total amount of water is also different. Liquids stand at the same height in communicating vessels, no matter what their shape. (See Fig. 21.) Hence we conclude that *liquid pressure is independent of the shape and area of the container.*

In conclusion, we may summarize the following LAWS OF LIQUID PRESSURE:

1. *Liquid pressure is directly proportional to the depth of the liquid.*
2. *Liquid pressure is directly proportional to the density of the liquid.*
3. *Liquid pressure is independent of the area or shape of the container; it is also independent of direction.*

**★32. Explain direct and inverse proportion.** The terms *direct proportion* and *inverse proportion* are used frequently in stating facts and laws in physics. *Two quantities are directly proportional to each other when an increase*

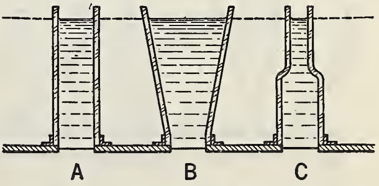


Fig. 20. Liquid pressure is independent of the shape or the area of the container.

*or decrease in one of them produces a corresponding increase or decrease in the other.* In the formula derived in Section 29, we observe that an *increase* in the depth of a liquid *increases* the pressure, and that an *increase* in the density of the liquid *increases* the pressure.

*Two quantities are inversely proportional to each other when an increase in one of them produces a corresponding decrease in the other.* If we squeeze a tennis ball, its volume becomes smaller. Suppose we refer to the formula for density,

$$D = \frac{W}{V}.$$

We observe that an *increase* in $W$ without any change in $V$ causes an *increase* in $D$; an *increase* in $V$ without any change in $W$ causes a *decrease* in $D$. Hence, the density of an object is *directly* proportional to its weight and *inversely* proportional to its volume.

Let us plot a graph or curve to show direct proportion, using data obtained by experiment.

Depth of 1 cm., pressure equals 1 gm.
Depth of 3 cm., pressure equals 3 gm.
Depth of 5 cm., pressure equals 5 gm.
Depth of 9 cm., pressure equals 9 gm.
Depth of 12 cm., pressure equals 12 gm.

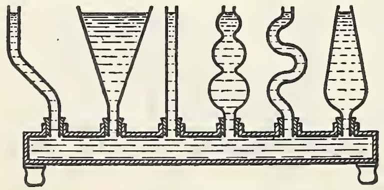


FIG. 21. Liquids in connecting vessels stand at the same height.

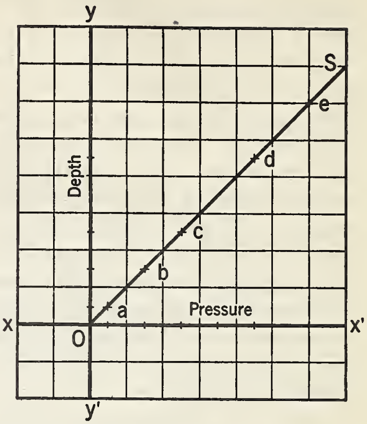


FIG. 22. The direct proportion curve shows that the pressure increases as the depth increases.

Suppose that we let $O$ represent the origin of the graph, Fig. 22, and measure off on the line $xx'$ distances equivalent to the various pressures. For convenience let us use one small space to represent one gram. Next let us measure off on the line $yy'$ distances *equivalent* to the depth in cm., using one small space to represent 1 cm. Point $a$ represents a pressure of 1 gm. at a depth of 1 cm.; point $b$ represents a pressure of 3 gm. at a depth of 3 cm. In a similar manner we locate the points $c$, $d$, and $e$, and draw a line from the origin of the curve through all these points. This line, $OS$, is a curve of *direct proportion.*

**33. How can one find the total force on the bottom of a container?** We have learned that the *pressure* which a liquid exerts, on the bottom of a containing vessel, for example, equals the product of the depth and the density. While engineers refer to pressure in lb. per *sq. in.*, it will generally be more convenient for us to use the *sq. ft.* as the unit area. On the bottom of a tank containing water 10 ft. deep, the pressure on each *sq. ft.* equals depth (10 ft.) × density (62.4 lb. per cu. ft.), or 624 lb. per *sq. ft.* This is equal to 4.33 lb. per *sq. in.*

NOTE. While the following suggestion may not accord with *formal* mathematics, yet it does aid the beginner. Let us write,

$d = 62.4 \frac{\text{lb.}}{\text{cu. ft.}}$. As we multiply, 10 ft. $\times\ 62.4 \frac{\text{lb.}}{\text{cu. ft.}}$, suppose we assume that the denomination *ft.*, which in the numerator represents depth, will change the *cu. ft.* in the denominator to *sq. ft.* By cancellation, $10\ \cancel{\text{ft.}} \times 62.4 \frac{\text{lb.}}{\cancel{\text{cu. ft.}}\ (\text{sq. ft.})}$. Whence, pressure $= 624 \frac{\text{lb.}}{\text{sq. ft.}}$.

Since pressure is the force acting on *unit area*, to find the *total force* acting on the bottom of a vessel we merely multiply the *area* by the *pressure.* Stated algebraically,

*total force* = *area* × *pressure*, or

*total force* = *area* × *depth* × *density.*

By using $F$ to represent total force, $A$ for area, $h$ for depth, and $d$ for density, the formula becomes,

$$F = Ahd.$$

PROBLEM. A box 10 ft. long, 8 ft. wide, and 6 ft. deep is full of water. Find the total force on the bottom of the box.

*Solution.* The area pressed upon is 10 ft. × 8 ft., or 80 sq. ft.; the depth of the water is 6 ft., and its density $62.4 \frac{\text{lb.}}{\text{cu. ft.}}$.

total force = area × depth × density.

total force $= 80 \times 6 \times 62.4 \frac{\text{lb.}}{\text{cu. ft.}}$. The answer is 29,952 lb.

NOTE. In the foregoing problem, suppose we assume that the *sq. ft.* of the area times *ft.* in depth completely *cancel* the cu. ft. in the denominator as follows: $80\ \cancel{\text{sq. ft.}} \times 6\ \cancel{\text{ft.}} \times 62.4 \frac{\text{lb.}}{\cancel{\text{cu. ft.}}}$. Therefore, the answer is 29,952 *pounds.*

PROBLEM. Find the total force on the bottom of a box 3 m. long, 2 m. wide, and 1 m. deep, if the box is full of water.

*Solution.* Changing m. to cm., we have 300 cm. × 200 cm. × 100 cm. The area pressed upon is 300 cm. × 200 cm., or 60,000 sq. cm.; the depth is 100 cm.; and the density is $1 \frac{\text{gm.}}{\text{c.c.}}$.

By substituting in the formula, total force will equal $60{,}000 \times 100 \times 1 \frac{\text{gm.}}{\text{c.c.}}$. The answer is 6,000,000 gm. If we solve the problem by using meters, then we get 6 metric tons as our answer.

**★34. How can you find the total force on the side of a containing vessel, or against a dam?** Everybody knows the story of the Dutch boy at the dike. As he stopped the small hole in the dike, he was resisting the sidewise pressure of the sea. As the soil around our houses fills with water, the sidewise pressure may become great enough to push the water through our cellar walls. In building a dam, engineers must calculate the total force which the water will exert against the side of the dam. We know that in our calculations we must always use for the area the *area of the surface pressed upon.* We know, too, that pressure is independent of direction, but we must consider what depth to use.

Imagine that the room in which you are sitting is full of water. Its length is 15 ft.; its width is 12 ft.; and its ceiling is 8 ft. high. The area of the longer side of the room is equal to the length, 15 ft., multiplied by the height of the wall, 8 ft. The *area pressed upon* is 120 sq. ft. The water is 8 ft. deep at the floor; at the ceiling the water is 0 ft. deep. From Fig. 23 we see that

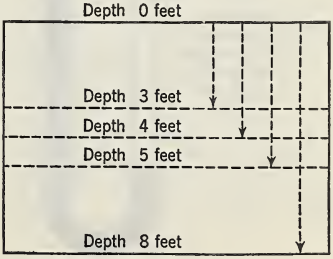


FIG. 23. The pressure against a vertical surface varies with the depth.

the depth varies. Halfway up the wall, the water is 4 ft. deep; 3 ft. from the floor, the water is 5 ft. deep; and 3 ft. from the ceiling, the water is 3 ft. deep. The *average depth* is 4 ft.

$$\left(\frac{0 + 3 + 4 + 5 + 8}{5} = 4.\right)$$

Since the depth of a vertical surface varies, we must use the *average depth*. Then the total force on the wall of the room = 120 sq. ft. (area) × 4 ft. (average depth) × 62.4 $\frac{\text{lb.}}{\text{cu. ft.}}$. The force is equal to 29,952 lb.

*In any case, total force equals the area of the surface pressed upon times the average depth times the density.* For *horizontal* surfaces the depth is uniform at all points. Hence, $F = Ahd$. For *vertical* surfaces, the average depth is usually equal to *half* the depth. Hence, $F = A\frac{h}{2}d$.

**35. How is pressure measured?** Occasionally the water pressure in some cities becomes low in dry weather. To be certain that the pressure is great enough to fight fires effectively, a pressure gauge of some kind is used. An *open manometer* is shown in Fig. 24. Here the pressure of the water is balanced against a column of mercury. The manometer, which is partially filled with mercury, is attached to the faucet and the water is turned on. The pressure is measured by the height of the mercury column $AB$. If the tube has a cross-sectional area of 1 sq. in., the weight of the mercury column in pounds equals the pressure of the water in lb. per sq. in. Sometimes a *closed manometer* is used, but more often water pressure is measured by means of a spring gauge, which is calibrated to read directly in pounds per square inch. (See Fig. 25.) The pressure of the water tends to straighten out the flat, curved tube, which is attached at one end to a lever geared with the pointer.

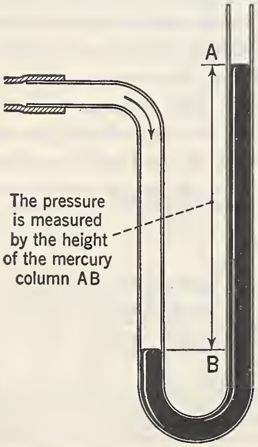

A
The pressure is measured by the height of the mercury column AB
B

FIG. 24. The open manometer may be used to measure pressure.

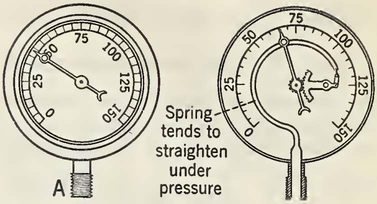


FIG. 25. The Bourdon pressure gauge. Sectional view at right.

The expression "head of water" or "water head" is in common use by engineers. If the *difference* of levels in communicating pipes is 144 ft., the water head is said to be 144 ft. Such a water head produces a pressure of 62.4 lb. per sq. in., because a water column of one sq. in. cross-sectional area and 144 ft. high has a volume of just one cubic foot. If we refer to Fig. 26, we can understand why the water head on the different floors of the same building is not the same.

**36. What are some applications of water pressure?** 1. *Water seeks its level.*

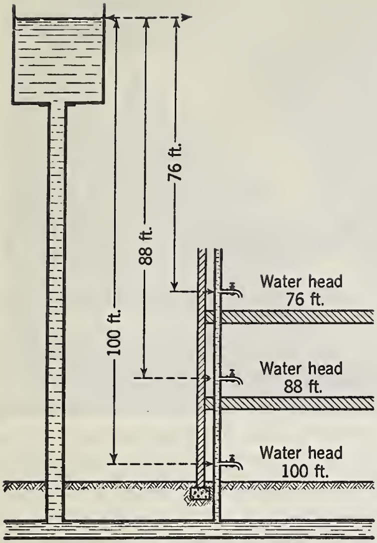


FIG. 26. The water head is greater at the lower floor. The effective pressure is least at the tap on the top floor.

Water stands at the same height in communicating vessels, whatever their shape or relative area. The water in the spout of a teakettle stands at the same level as the water in the kettle. If we picture the surface of the water in a tank as having momentarily the form shown in Fig. 27, we can understand why water seeks its level. The water heads at *A* and *B* are greater than at *C*. Hence the greater pressure at these points will cause the water to flow in the directions shown by the arrows until the surface is level. The water-gauge on a steam boiler is another application. (See Fig. 28.) If you have a steam boiler in your basement, the level of the water in the glass gauge shows the level of the water inside the boiler.

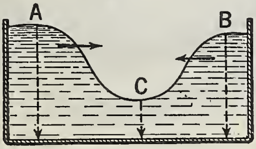


FIG. 27. Water flows until its surface becomes level.

The water supply for some cities is drawn from a reservoir higher than any part of the city itself. Since water seeks its level, it readily rises through the water pipes in the houses to the taps or faucets. If, however, part of a tall building happens to be higher than the level of the reservoir, then the upper floors of such a building will be without water and cannot have adequate fire protection. Such a building may be supplied from a tank on the roof or by means of a pump which forces the water to the highest parts of the building. Many cities are forced to install pumping stations. The pump forces water from the reservoir up into the standpipe, where it is stored. (See Fig. 29.) Sometimes a high-pressure pumping system is installed for fighting fires. (See Fig. 30.)

The *artesian well* is another example of the fact that water seeks its level. (See Fig. 31.) We have a layer of water-saturated gravel between two strata of impervious or non-porous rock. The water levels at *A* and *B* are higher than the level at *W*. Hence water

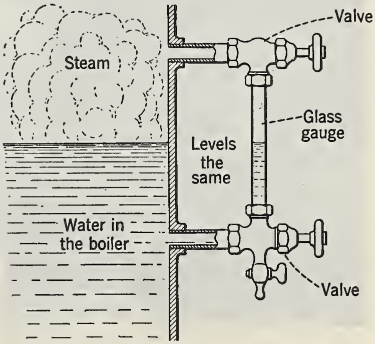


FIG. 28. Water in glass gauge stands at level of liquid in boiler.

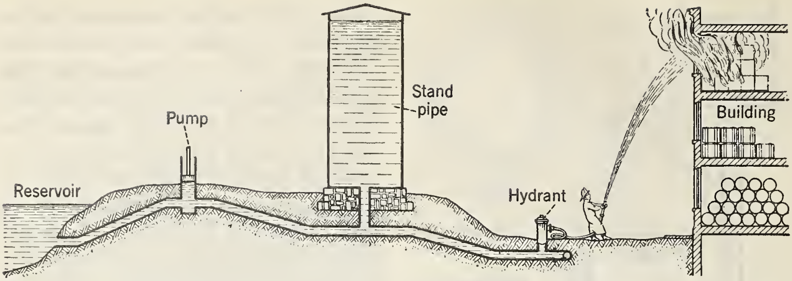


FIG. 29. Water from reservoir is pumped to standpipe. It flows to hydrant and exerts enough pressure to be effective in fighting fires.

gushes out to form a flowing well or fountain at $W$. (See Fig. 32.)

2. *Submerged bodies must withstand pressure.* Probably the bottom of our cellar wall is at least 4 feet below the water table when snow and ice are melting in the spring. That means that water is exerting a pressure of 4 × 0.433 lb. on every square inch of the bottom of our cellar walls. A pressure of 1.7 lb. per sq. in. may be sufficient to push the water through the pores of the concrete wall and cause water to enter our cellar.

*Courtesy of the Seagrave Corporation*

FIG. 30. To fight city fires effectively, high water pressures must be used.

Submarines must have very strong walls to resist the crushing force of the water, since the pressure increases as the submarine sinks deeper and deeper. The hull of an ocean vessel may extend about 30 feet beneath the surface of the sea. It must be made very strong to resist such pressure.

If we dive to a depth of 10 feet, the water pressure on every square inch of our body is more than 4 lb. At 100 feet the pressure increases to more than 40 lb. per sq. in. Deep-sea divers have descended to a depth of more than 300 feet.

3. *Total force as related to construction work.* Before building cisterns, tanks, standpipes, dams, and canal locks, the engineer must compute the pressure or the total force to which these structures will be subjected. The amount of material used in construct-

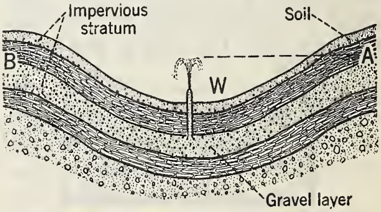
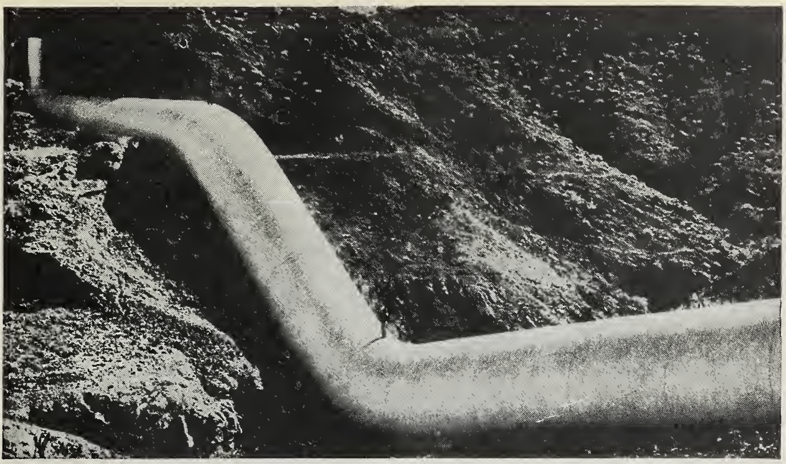
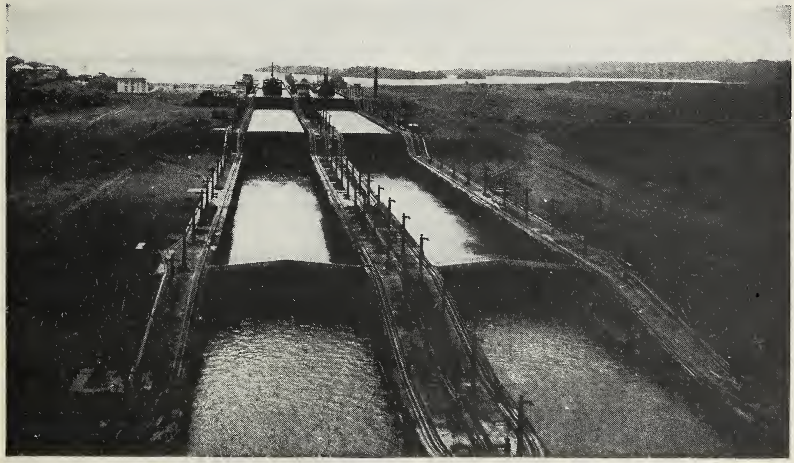


FIG. 31. Water from gravel layer forces water out through the opening at $W$.



*Courtesy of the Metropolitan Water District*

Fig. 32. This 16-foot aqueduct carries water from the Colorado River 392 miles to Los Angeles and other cities in Southern California. It carries about a billion gallons of water daily. Having a capacity of about 400 barrels per second, it dwarfs other famous aqueducts, ancient and modern. It consists of tunnels, conduits built of concrete, steel pipe, and canals lined with concrete. At some places it crosses elevations more than 1600 feet in height. Notice the appearance of the men standing on the aqueduct.



*Courtesy of the War Department*

Fig. 33. The Panama Canal locks are 1000 ft. long, 110 ft. wide, and the minimum depth of the water is 41 ft. The steel gates are 7 ft. thick and 65 ft. long. They are from 47 to 82 ft. in height. They weigh from 300 to 600 tons each. The building of the Panama Canal is one of the triumphs of engineering. The Canal Zone had to be freed from mosquitoes. The heat was terrific, and landslides were common. The manufacturers of the steam shovel boast that their machines made the digging of the Canal possible.

ing dams for storage reservoirs is enormous. Fig. 33 gives an idea of the enormous strength that canal locks must have, to withstand the total force of the water when the gates are closed.

## QUESTIONS

1. Explain why water flows down hill.

2. Why is it difficult to keep water out of cellars?

3. Does water flow faster from a tap in the basement than from a similar tap on the third floor? Explain.

4. Two types of standpipes are shown in Fig. 34. If the water stands at the same height in both, how do the pressures compare?

5. Should a dam be made thicker at the bottom or at the top? Give a reason for your answer.

6. Three Pascal vases are made like those shown in Fig. 20. The area of the base is the same in all three cases. They are filled to the same depth with water. Compare the pressures in each case. How do you think the total force on the bottom in each case compares with the weight of the liquid?

7. How does your city get its water supply? Is the reservoir high enough to furnish sufficient pressure for fighting fires?

8. The pressure at the point of a phonograph needle may amount to several tons per sq. in. Explain how this is possible, since the reproducer weighs only a few ounces. Why does the heel of a woman's shoe sink so deeply into soft ground?

9. Why does a liquid exert pressure? Upon what factors does the intensity of liquid pressure depend? Of what factors is liquid pressure independent?

10. A dam is built across a river. Does the length of the river affect the total force of the water against the breast of the dam? Give reasons for your answer.

## PROBLEMS

### Group A

1. What is the pressure in gm. per sq. cm. of a column of water 4 m. high?

2. What is the pressure of a column of mercury 76 cm. high? (Density of mercury is 13.6 gm. per c.c.)

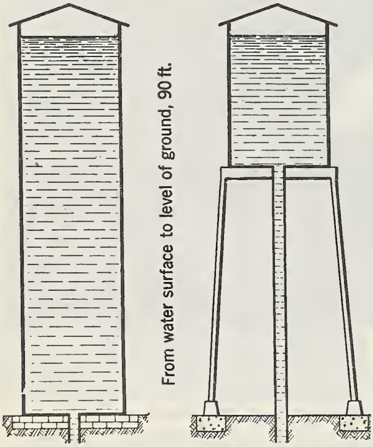


Fig. 34. Two types of standpipes.

3. How high a column of water will be needed to exert the same pressure as the column of mercury of Problem 2?

4. A man dives into sea water (density is 64 lb. per cu. ft.) to a depth of 300 ft. What is the pressure upon each square foot of his body? On each square inch?

5. The surface of the water in a standpipe is 196 ft. above the level of a faucet. What is the pressure at the faucet?

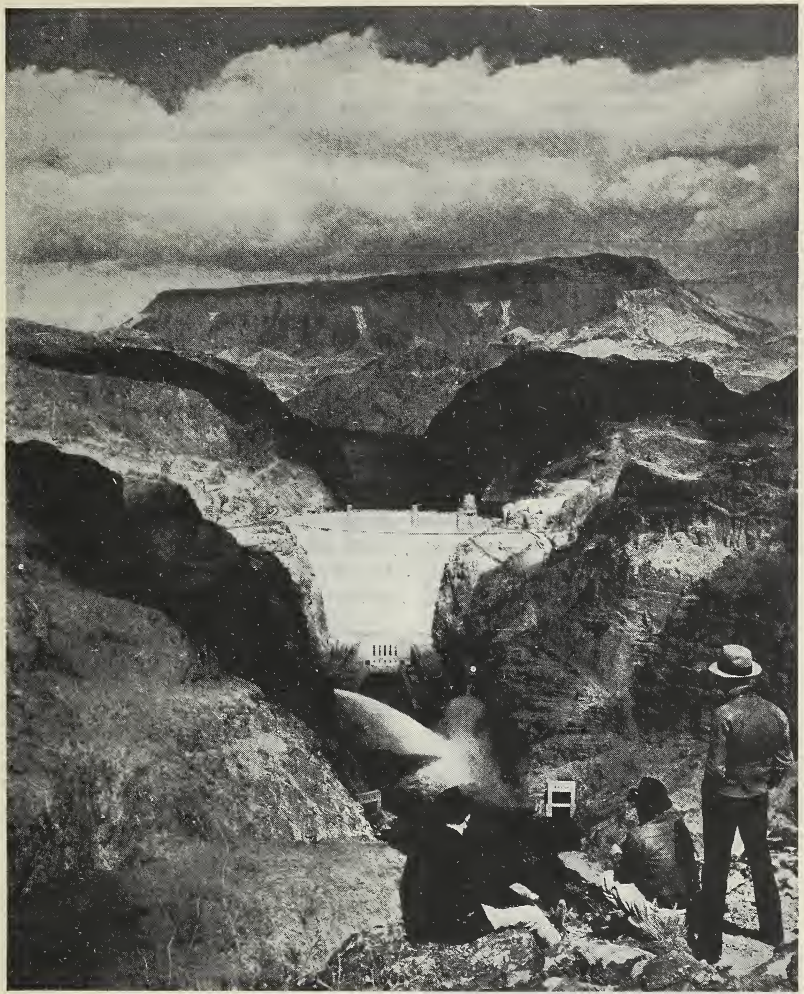
6. What pressure is available when the water head is 500 ft.?

7. A tank 8 ft. long, 8 ft. wide, and 10 ft. deep is filled with water. Calculate the total force on the bottom of the tank.

8. Calculate the total force on one side of the tank of Problem 7.

9. A vat 2 m. long, 160 cm. wide, and 1200 mm. deep is filled with sulfuric acid, density 1.8 gm. per c.c. Calculate the total force on the bottom of the vat. Calculate the total force on one of the longer sides.

10. The elevation of the lake above



*Courtesy of the Department of the Interior*

FIG. 35. Boulder Dam, built in Black Canyon, impounds water for irrigation purposes and for furnishing some 1,835,000 horsepower of electrical energy. The dam is 726 ft. high and the length of its crest is 1200 ft. The base of the dam is 650 ft. thick. It is the highest dam in the world, and it took nearly five years to complete the work. The thickness at the top is 45 ft. A total of 4,360,000 cu. yd. of concrete was used in its construction. To make the concrete, 5,500,000 barrels of cement were required. Lake Mead, which is formed by impounding the flood waters of the Colorado River, is the world's largest artificial lake, being 115 miles long, and 2 miles wide. The powerhouse is equipped with 15 generators of 115,000 horsepower each, and two of 55,000 horsepower each.

Boulder Dam is 530 ft. above the surface of the river below the dam. What is the pressure at the base of the dam? Can you see why it is necessary to make the base of the dam of concrete 650 ft. thick? (See Fig. 35.)

11. The breast of a dam is 50 ft. long; its vertical height is 40 ft. Find the total force against the dam when the water stands level with the top.

12. Some parts of the ocean are at least 30,000 ft. deep. What is the pressure at that depth? What would be the force upon your body assuming its area is 10 sq. ft.?

### Group B

13. What water head is needed to give a pressure of 500 lb. per sq. in. for use in fighting city fires?

14. The volcano Mauna Loa is 13,760 ft. high. Assuming that the crater is full of molten lava, density of 175 lb. per cu. ft., what is the pressure at the base of the volcano?

15. A rectangular tank 60 ft. long, 30 ft. wide, and 10 ft. deep is filled with sea water. Calculate the total force on the bottom of the tank.

16. The walls of a vacuum bottle can withstand a pressure of 400 lb. per sq. in. To what depth in the ocean must such a bottle be sunk to be crushed by the water pressure?

Wide World

Fig. 36. In this thick-walled bathysphere Dr. William Beebe has made several descents into the ocean to study the animals that inhabit the deep seas. He has reached a depth of 3028 ft.

17. A swimming tank is 100 ft. long and 30 ft. wide. At one end the water is 4 ft. deep and at the other end it is 8 ft. Calculate the total force upon each end of the tank, if it is filled with fresh water.

18. What force is required to hold a board 4 ft. long and 2 ft. wide tightly against a hole in the side of a ship, if the top of the hole is 20 ft. below the surface of the ocean?

19. Beebe descended in his bathysphere to a depth of 3028 ft. near Bermuda. Calculate the pressure against the walls of the bathysphere. (See Fig. 36.)

20. A circular tank 20 ft. in diameter and 15 ft. deep is full of gasoline, density 44 lb. per cu. ft. Find the total force on the bottom of the tank.

21. A cistern is 10 ft. in diameter and 10 ft. deep. What is the total force on the bottom, if it is full of water?

22. One of the gates for the Panama Canal is 65 ft. long. If the water stands 60 ft. higher on one side than it does on the other, what is the force on the gate?

23. A diver descended in Lake Michigan to a depth of 420 ft. Calculate the pressure on his body.

24. A box 4 ft. long, 3 ft. wide, and 2 ft. deep, is filled with mercury, having a density of 846 lb. per cu. ft. Calculate the total force on the bottom of the box. What is the force on one side of the box?

25. A glass tank is filled with sulfuric acid, density equal to 1.8 gm. per c.c. What is the pressure in kgm. upon each sq. cm. at a depth of 2 meters?

26. What is the total force against a gate 4 ft. square at the bottom of one side of a dam, if the bottom of the gate is 22 ft. deeper than the surface of the water on that side of the dam?

## 2. Pressure Applied to Liquids

**37. How do liquids transmit pressure?** The liquid pressure which we have been studying may be called *weight pressure* since it is due to the weight of the liquid itself. Solids also exert pressure on account of their weight, but not in a sidewise direction. If we put one end of a meter stick against the floor and push on the other end, it *transmits the pressure* to the floor in the direction in which the force acts. Since the stick is rigid, it transmits the pressure in *only one* direction. Suppose that we put a stopper in one end of an iron pipe and completely fill the pipe with water. As a second stopper is pushed into the open end of the pipe, the first stopper is pushed out because the pressure is transmitted to it by the liquid in the pipe. Liquids are not easily compressed and readily transmit pressure. Now suppose that we drill several small holes in the pipe and repeat the experiment. As the second stopper is pushed into the pipe, the liquid squirts out through the holes, proving that pressure applied to a confined liquid is *transmitted in all directions.* This is what we might expect if we pause to consider that the molecules of liquids move freely and slide over one another readily.

For the same reason we would expect gases to transmit applied pressure in all directions. When we inflate an automobile tire, pressure is applied at the valve stem to the air confined within the tire. Since all parts of the tire become equally hard, we may assume that this pressure is *transmitted equally in all directions.*

**38. What happens when external pressure is applied to confined liquids?** A farm hand went to the well, filled a jug with water, inserted the stopper, and hit the stopper a sharp blow with the palm of his hand. The bottom fell out of the jug, much to his astonishment. Let us inquire what really happened. Fig. 37 represents the jug filled with water. As the stopper was driven into the jug by the force of the blow, *its pressure upon the confined liquid was transmitted equally in all directions.* For convenience, let us assume that the neck of the jug had an area of exactly 1 sq. in., and that 10 lb. of force were used in driving the stopper into the jug. That means that *every* square inch of the inside surface was subjected to a pressure of 10 lb., *in addition to the weight pressure.* If the bottom of the jug had an area of 40 sq. in., the total force acting upon it must have reached the astonishing total of 400 lb. The bottom of the jug was not strong enough to withstand so great a force.

**39. What is Pascal's law?** The farm hand just mentioned had never heard of Pascal's experiments. Blaise Pascal was a French physicist who devised Pascal's vases to show that *weight pressure* of liquids is directly proportional to their depths, but independent of the

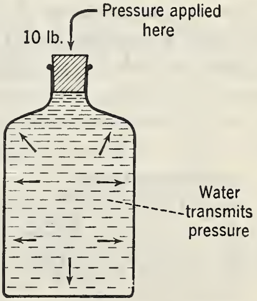


FIG. 37. Bottle to be used to demonstrate Pascal's law.

shape of the container. But Pascal also devised an experiment to study the transmission of pressure by liquids when pressure from *outside* is applied to their surfaces. He fitted pistons in openings in the sides of a box filled with water, just like the cork in the jug of Section 38. One opening had an area 100 times as large as the other and the pistons fitted the openings tightly. (See Fig. 38.) Pascal then found that *one man*, pushing against the small piston, could hold that piston against the force of *100 men* pushing against the large piston.

His comment is as follows: "Hence it follows that a vessel full of water is a new principle in mechanics, and a *new machine for multiplying forces* to any degree we choose, since one man will by this means be able to move any given weight."

This principle, which is known as PASCAL'S LAW, may be stated as follows: *Pressure applied anywhere to a body of confined or inclosed fluid is transmitted with undiminished force in every direction. This pressure acts at right angles to every portion of the surface of the container, with equal force upon equal areas.* Fluids comprise both liquids and gases; hence Pascal's law applies to both.

**40. How is transmission of liquid pressure used to multiply force?** From Pascal's law, we are led to the following conclusion: If $A$ of Fig. 39 has an area of 1 sq. in. and $B$ an area of 100 sq. in., a weight of 1 lb. lying on the piston $C$ will just balance a weight of 100 lb. on the piston $D$. A force *slightly* in excess of 1 lb. acting downward on the small piston will lift the weight of 100 lb. upon the large piston. From these observations, it is easy to see how it is possible to construct a mechanical device for multiplying force. If we make the large opening 1000 times the area of the small one, the small force on the small piston is multiplied by 1000.

The pupil must never forget one important fact. As we *multiply force* by the use of any mechanical device, we diminish correspondingly the *distance and speed* of the load. In other words, *what is gained in force is lost in speed and distance.* Suppose we force the piston $C$ down 10 in.; just 10 cu. in. of water will be forced from $A$ into $B$. The 10 cu. in. of water that are forced into the large cylinder will spread out over an area of 100 sq. in. Therefore it will raise its level and lift the large piston $\frac{10}{100}$, or 0.1 in. In the time required for $C$ to move 10 in., $D$ moves only 0.1 in., just 0.01 as far as $C$. The force of 1 lb. is multiplied 100 times by this device, but the object to be lifted on the large piston moves 0.01 as fast as the force applied to the small piston. In all mechanical devices, *the product of the acting force multiplied by the distance through which it moves equals the product of the resisting force multiplied by the distance through which it*

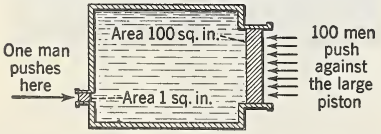


FIG. 38. How man can use a machine to multiply his feeble efforts.

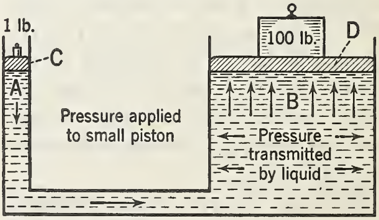

1 lb.
C
A
Pressure applied to small piston
100 lb.
D
B
Pressure transmitted by liquid

FIG. 39. Pressure applied to a confined liquid is transmitted equally in all directions.

*moves*. This is the *general law of frictionless machines.* Applied to this particular case, 1 lb. moving 10 in. is equivalent to 100 lb. moving 0.1 in.

**41. How does the hydraulic press work?** The commercial hydraulic press is an application of Pascal's principle. By reference to Fig. 40, we may explain the operation of such a press. There are two cylinders, a small one and a large one. In each one there is a piston which fits so tightly that the liquid cannot be forced past it. A lever is attached to the small piston. As the small piston is pushed down, some of the oil or water from the small cylinder is forced over into the large cylinder *B*, and the piston is lifted a trifle. As the lever is worked up and down, it continues to pump the liquid from the reservoir, and force it into the cylinder *B*. When the pressure is to be released, a valve not shown in the diagram is opened to let the liquid flow from *B* back into the reservoir.

The hydraulic press is used for baling cotton, paper, etc., squeezing the juice from apples and other fruits, expressing oil from seeds, punching holes in steel plates, embossing metals, and lifting enormous weights.

**42. What is meant by mechanical advantage?** Man often uses a machine to multiply his feeble efforts. Such a machine gives him an advantage. Suppose we assume a frictionless machine in which an *acting force* of 1 lb. can exactly counterbalance a *resisting force* of 5 lb. We say the *mechanical advantage* of that machine is 5, because the resisting force is five times as great as the acting force. Let us call the resisting force the *resistance R*, and the acting force the *effort E*. Then the mechanical advantage (M.A.) equals $\frac{\text{resistance}}{\text{effort}}$; or, M.A. $= \frac{R}{E}\cdot$ The mechanical advantage of any machine may also be found by measuring the distance the effort moves and the distance the resistance moves in the same time. Then,

$$\text{M.A.} = \frac{\textit{distance effort moves}}{\textit{distance resistance moves}}.$$

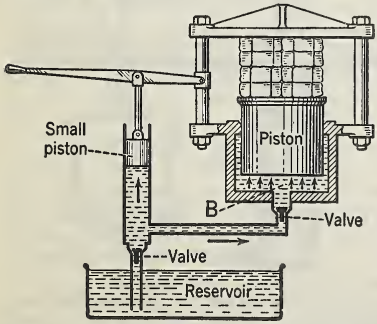


FIG. 40. The hydraulic press finds many uses.

Exclusive of the advantage of the lever, the mechanical advantage of the hydraulic press is equal to the area *A* of the large piston divided by the area *a* of the small piston. From your geometry, you learned that the *areas of two circles are proportional to the squares of their diameters.* Hence the formulas:

$$M.A. = \frac{A}{a}, \text{ or } M.A. = \frac{D^2}{d^2}\cdot$$

We may use the proportion,

$$E : R = a : A, \text{ or } E : R = d^2 : D^2.$$

PROBLEM. A force of 500 lb. is applied to the small piston of a hydraulic press. Its diameter is 2 in. What resistance can be counterbalanced on the large piston, which is 40 in. in diameter?

*Solution.* The M.A. $= \frac{(40)^2}{(2)^2}$, or 400. If the machine multiplies the effort by 400, then 500 lb. of effort can counterbalance 400 × 500 lb., or 200,000 lb. Or, we may use the formula, $E : R = d^2 : D^2$. Whence $500 : x = (2)^2 : (40)^2$. $x = 200{,}000$ lb.

**43. How do hydraulic brakes work?** Many automobiles are now equipped with hydraulic brakes, which are applications of Pascal's principle. The force applied to the brake pedal acts upon a master piston, from which it is transmitted through the oil in strong tubes to the brake piston. (See Fig. 41.) The pressure of the liquid in the brake piston pushes the brake shoes apart so that they will exert friction against the brake drum. A spring pulls the shoes together again when the brakes are released. If the pistons all have the same diameters, the pressure applied to the brakes on all wheels will be the same, and skidding is not likely. It is possible, too, to have the front-wheel brakes do a greater part of the braking, if desired. The newer cars follow this practice.

**44. There are other applications of Pascal's law.** Of course we are making use of Pascal's law when we inflate a tire. The *hydraulic jack* is used for lifting very heavy loads through a short distance. In many cases, *dentists'* and *barbers'* chairs are lifted by the use of hydraulic pressure. *Hydraulic elevators* operate by the use of water pressure acting upward on the bottom of a large piston beneath the elevator cage.

The *automobile hoist*, Fig. 42, is a common application of Pascal's principle found at filling stations. Compressed air is applied to the surface of oil which then transmits the pressure to the lower end of the hoisting piston. In this manner a car weighing one or two tons can be hoisted easily.

## QUESTIONS

1. Do you think that there is any truth in the claim of manufacturers of hydraulic brakes that they are easily equalized?

2. Assuming that the story of the Dutch boy at the dike is true, how could he hold back the waters of the North Sea?

3. What would one gain by applying the acting force to the large piston of a hydraulic press and the resisting force to the small piston? (Use is made of this reversed application in launching airplanes from battleships.)

4. For sinking hostile submarines during the World War depth-bombs were used. They sank to a given depth before exploding. How did the transmission of liquid pressure make them effective in rupturing the walls of the submarine?

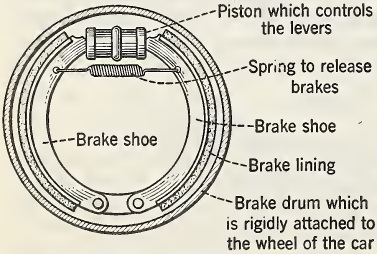

Piston which controls the levers
Spring to release brakes
Brake shoe
Brake shoe
Brake lining
Brake drum which is rigidly attached to the wheel of the car

Fig. 41. Some internal-expanding brakes operate by means of hydraulic pressure.

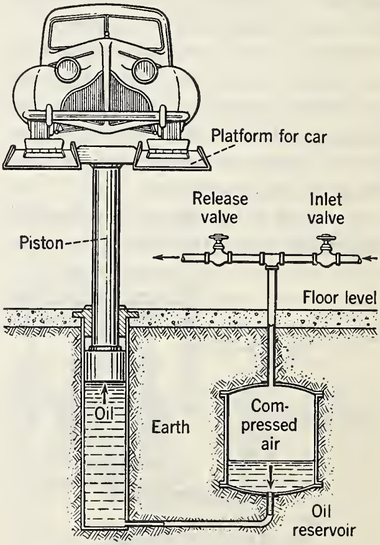

Platform for car
Release valve
Inlet valve
Piston
Floor level
Oil
Earth
Compressed air
Oil reservoir

Fig. 42. The service station attendant uses Pascal's law to hoist a car and make work underneath the car more convenient.

5. Why is the explosion of dynamite beneath the surface of water so destructive to fish?

6. Is it possible to have a mechanical advantage of speed? Give a reason for your answer.

7. A man bought a lawn roller which was to be filled with water to give it the necessary weight. When he screwed the end of his garden hose into the opening in one end of the roller and turned on the water, one end of the roller was pushed out. Explain.

8. Why is it a good idea not to fill a vacuum bottle entirely full of liquid before putting in the cork?

## PROBLEMS

### Group A

1. What is the mechanical advantage of a hydraulic press in which the area of the large piston is 500 times the area of the small piston?

2. What is the mechanical advantage of a hydraulic press if the diameter of the large piston is 15 times that of the diameter of the small piston?

3. The small piston of a hydraulic press has an area of 1 sq. in. The area of the large piston is 200 sq. in. What is the mechanical advantage of the press? What force must be applied to the small piston to balance a weight of 10 tons on the large piston?

4. The diameters of the two pistons of a press are 1 in. and 8 in. respectively. What force is needed to lift a weight of 144 tons?

5. The diameter of the inlet pipe of a hydraulic hoist is 1 in. The piston has a diameter of 10 in. What force at the inlet must be used to lift a car weighing 4000 lb.?

6. By the use of a hydraulic press, 100 lb. must lift 40,000 lb. What mechanical advantage is needed? If the diameter of the small piston is 1 in., calculate the diameter of the large piston.

7. The two pistons of a hydraulic press have diameters of 2 in. and 30 in. respectively. If a force of 400 lb. is applied to the small piston, what load applied to the large piston can be lifted?

### Group B

8. The two pistons of a press have areas of 1 sq. in. and 132 sq. in. respectively. If the large piston moves with a velocity of 0.5 ft. per second, what velocity will the small piston have, measured in feet per second? What is the velocity in mi. per hr.?

9. A cubical box is 20 cm. on a side. To the top of the box a tube 1 sq. cm. in cross-sectional area and 180 cm. long is attached. Both are filled with water. Calculate the total force upon the bottom of the box, upon each side, and the upward force on the top of the box. (See Fig. 43.)

10. Suppose that we fit the tube of Problem 9 with a piston which is watertight and apply a force of 500 gm. to the piston. Calculate the total force upon the bottom of the box. (Include force due to weight pressure.)

11. An 80-kgm. man stands upon the platform *P* (Fig. 44), which is 25 cm. by 40 cm. At what height must the water stand in the tube to balance the weight of the man? Does the diameter of the tube have any effect upon the answer?

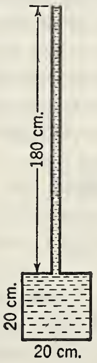


FIG. 43. Total force.

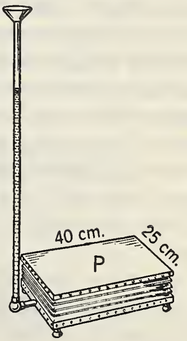
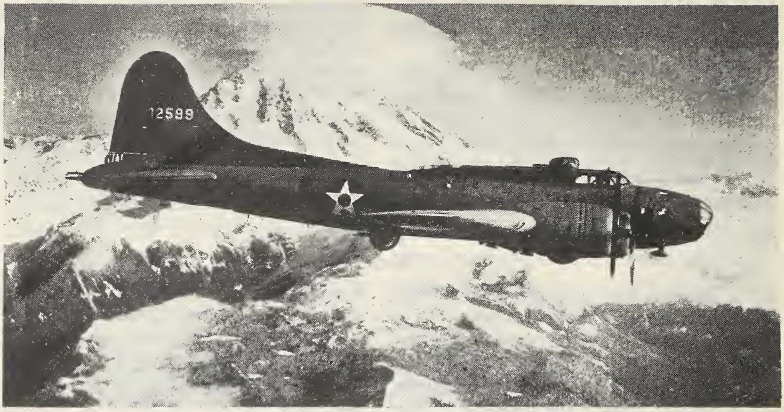


FIG. 44. Hydrostatic bellows.



*Courtesy of Boeing Aircraft Company*

FIG. 45. The Boeing B–17E Flying Fortress is a powerful United States bomber.

## 3. Archimedes' Principle

**45. What is buoyancy of liquids?** Pieces of cork and sticks of wood float on water. If the lungs are filled with air, the human body floats on water. Such facts furnish evidence that water exerts an upward pressure, or *buoyant force*, upon objects immersed in it. An object will float if the buoyant force of the water is greater than the weight of the object itself. (See Fig. 45.) Objects denser than water, even though they sink readily, appear to lose a part of their weight when submerged. For example, a man can lift a larger stone under water than he can possibly lift in air, because the buoyant force of the water lifts part of the weight. *The upward force which any liquid exerts upon a body submerged in it is called its buoyancy.*

**46. How is buoyancy measured? Archimedes' principle.** Hiero, tyrant of Syracuse, ordered a crown made of pure gold. He handed the crown to Archimedes, asking him to determine whether any other metal had been used in its construction. Archimedes was puzzled to find a solution to this problem. While at his bath, he observed the buoyant effect of the water upon his body, and that the water rose in the tub as his body sank in the water. Then it occurred to him that he could use the buoyant effect of water upon the crown and upon pure gold to solve his problem. He is said to have rushed through the streets, shouting "Eureka, Eureka," meaning "I have found it." He had found the solution to his problem, for he reasoned that the buoyant force on his body must be equal to the weight of water displaced. (See Fig. 46.)

Let us perform a simple experiment and then see how the principle worked out by Archimedes helped him to solve Hiero's problem. The overflow can shown in Fig. 47 is filled with water up to the spout. A block heavier than water is weighed, first in air, and then in water. The difference between the

FIG. 46. Archimedes (B.C. 287–212) was born in Syracuse, Sicily. His works on arithmetic, plane and solid geometry, and mechanics are still extant. He applied mechanics to such machines as the lever, the pulley, and the screw. He is best known through the principle that bears his name. When the city of Syracuse was captured after a long siege, Archimedes was killed by a Roman soldier.

two weights is the *loss of weight in water*. The block is then lowered into the overflow can. All the water which overflows, which just equals in volume the volume of the block, is caught and weighed. If the work was carefully done, we find as did Archimedes that the weight of the water displaced by the block exactly equals its loss of weight in water. This PRINCIPLE OF ARCHIMEDES may be stated as follows: *A body immersed in a fluid loses as much weight as the weight of the fluid it displaces.*

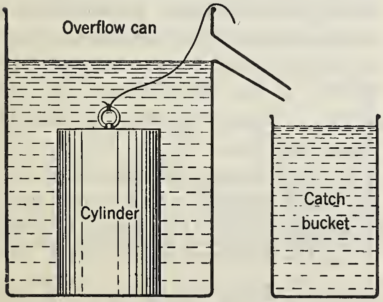


FIG. 47. Overflow can with dense block.

By applying this principle, Archimedes could compare the density of the crown with the density of a block known to be pure gold. Since gold is one of the densest of the metals, a piece of gold having a definite weight would have a smaller volume and would displace less water than a piece of silver of the same weight. For example, 1 lb. of gold displaces less water than 1 lb. of silver because its bulk is smaller. The relative volumes would be proportional to the losses of weight in water. Therefore, when Archimedes found that the crown lost more weight in water than the same weight of pure gold did, he knew that the crown was an alloy of some lighter metal.

**47. How can one test Archimedes' principle?** Suppose we submerge in water a cubical block, 10 cm. on a side, to such a depth that its upper surface *A* is just 10 cm. below the surface of the water. (See Fig. 48.) The total *downward* force on the upper surface of the block equals 1000 gm. (Area = 100 sq. cm.; depth = 10 cm.; density = 1 gm./c.c.) The total *upward* force on the surface *B* is 2000 gm. (Note that the surface *B* is 10 cm. deeper than *A*, or 20 cm.) The upward force at *B* exceeds

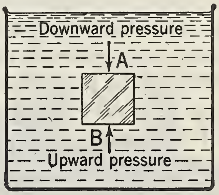


FIG. 48. Buoyancy equals the difference between the upward and the downward force.

*Courtesy of Roy Fitzsimmons*

FIG. 49. An iceberg floats with about nine-tenths of its volume beneath the surface of the water. If the iceberg rises 200 ft. above the surface, it will extend 1800 ft. beneath.

the downward force at *A* by 1000 gm., and this block would lose 1000 gm., if weighed first in air and then in water.

The volume of a cubical block 10 cm. on a side is 1000 c.c. Since two things cannot occupy the same place at the same time, the block must displace 1000 c.c. of water. Since 1 c.c. of water weighs 1 gm., 1000 c.c. of water will weigh 1000 gm. Therefore, the block displaced 1000 gm. of water. But the buoyant force of the water on the block was also 1000 gm. Hence we may use the facts we learned concerning total force in liquids to prove that the *buoyant force which a liquid exerts upon a submerged body is equal to the weight of liquid the body displaces.*

The student should compute the buoyancy when the *upper* surface of the block is submerged to a depth of 20 cm. below the surface of the water.

**48. What are the principles of flotation?** From the preceding section, we find that the buoyant force upon a submerged body is exactly equal to the weight of the liquid displaced. If the submerged body weighs more than an equal volume of displaced liquid, it will sink. For example, suppose the block used in the preceding section weighs 1200 gm. The buoyant force of the water was only 1000 gm. Hence an additional upward force of 200 gm. would have to be used to keep the block from sinking. It loses 1000 gm. of its weight in water, but 200 gm. of its weight are unbalanced.

Suppose, however, that the block weighs in air only 800 gm. The buoyant force when the block is completely submerged is 1000 gm. Such a block, if pushed under water and then released, would rise to the surface, because the upward force of the water is 1000 gm., and the downward force due to its weight is only 800 gm. To keep such a block submerged, an additional force of 200 gm. would have to be used. The iceberg of Fig. 49 displaces its own weight of water before it is entirely submerged.

Let us use one more example. A person whose volume or bulk is just 2 cu. ft. weighs 130 lb. If he jumps into sea water, the density of which is 64 lb./cu. ft., he will sink. The 2 cu. ft. of water displaced would buoy him up with a force of 128 lb., but his weight is 130 lb. It would take 2 lb. of force to keep him from sinking. Now suppose he uses just exactly 1 cu. ft. of cork as a life preserver. The cork weighs 15 lb. Now his total volume (body and cork) is 3 cu. ft., and the weight of water displaced would be 192 lb. His total weight (cork included) is 145 lb. Hence, it would need an additional force of 47 lb. to push him under water.

We may summarize the LAWS OF FLOTATION as follows: 1. *A body sinks in a fluid, if the weight of the fluid it displaces is less than the weight of the body.*

2. *A submerged body remains in equilibrium, neither rising nor sinking, if the weight of the fluid it displaces exactly equals its own weight.*

3. *If a body when submerged displaces a weight of fluid greater than its own weight, it will rise and float with a part of its volume above the surface.* Hence, a *floating* body displaces its *own* weight of liquid.

**49. How do floating objects behave?** If we place blocks of different kinds of light material on water, as shown in Fig. 50, we find that some sink deeper than others as they float. Suppose we select cubical blocks 10 cm. on a side. The volume in each case is 1000 c.c. Block *A* represents a piece of balsa wood. Because it is only about one-eighth as dense as water it finds use in making model airplanes and for making floats for persons learning to swim. Block *B* represents a piece of cork, density 0.24 gm./c.c. Its weight is 240 gm. Hence it must displace 240 gm., or 240 c.c., of water in order to float. When such a block is placed on the surface of the water, it will sink until 240 c.c. are submerged. This equals 0.24 of its volume, the same fraction as the density. Block *C* has a density of 0.75 gm./c.c. Since its weight is 750 gm., it will sink in water until 750 c.c. of its volume are submerged. The fractional part submerged is 0.75, the same fraction as the density. *D* represents a block of ice, having a density of 0.92 gm./c.c. Such a block weighs 920 gm., and it will sink until it displaces 920 c.c. of water. As ice floats in water, 0.92 of its volume is beneath the surface.

If we lower block *B* into gasoline, which has a density of only 0.7 gm./c.c. it will sink deeper into the liquid before it displaces enough gasoline to equal its own weight; 240 gm. ÷ 0.7 gm./c.c. = 343 c.c., the volume of gasoline needed to weigh 240 gm. Hence 343/1000 of the volume, or approximately $\frac{1}{3}$, is submerged, when cork floats in gasoline.

Aluminum, iron, and even lead will float in a very dense liquid like mercury. The fractional part submerged is proportional to their relative densities. (See Fig. 51.)

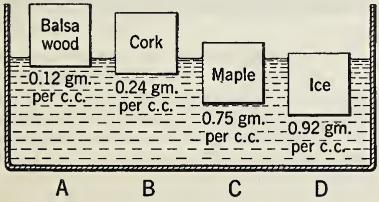


FIG. 50. Some floating objects sink more deeply than others.

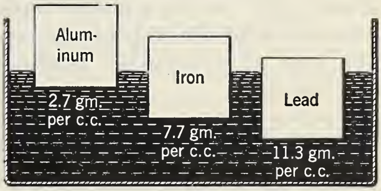
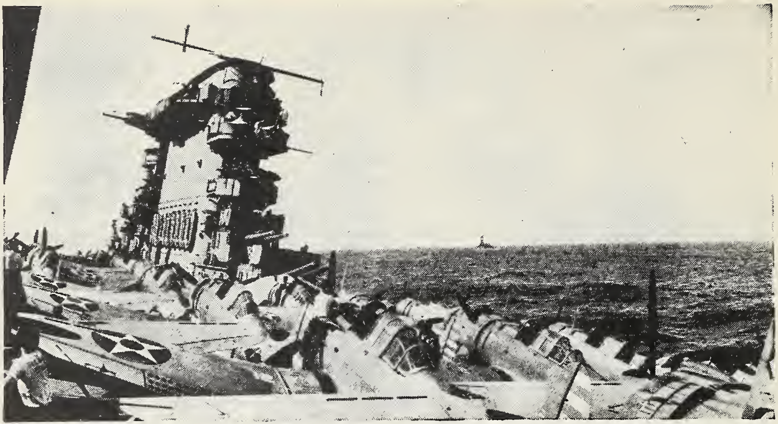


FIG. 51. Many metals will float in the dense liquid mercury.



Press Association, Inc.

FIG. 52. Planes are lined up on the deck of this United States Navy aircraft carrier which is plowing through heavy seas on offensive patrol duty in the Pacific.

**50. What are some applications of Archimedes' principle?** The whole science of shipbuilding depends upon Archimedes' principle and the laws of flotation. A ship that weighs 4000 tons and carries a cargo of 8000 tons must be so proportioned as to length, breadth, and depth that it will displace 12,000 tons of water. Some of our large battleships displace 45,000 tons of water. (See Fig. 52.) The *Normandie* has a registered tonnage of 83,423. For every 64 lb. of weight an ocean vessel can carry, one cu. ft. of sea water must be displaced. To displace the 166,846,000 lb. which the *Normandie* needs to float, it is no wonder that she must be 981.3 ft. long, 117.8 ft. wide and have a total depth of 57.5 ft. The pontoon bridge and the floating dry dock are other applications of Archimedes' principle. (See Fig. 53.)

A person can float in salt water more easily than in fresh water, because the density of the salt water is slightly greater. The use of the ordinary life preserver is an application of the third

Press Association, Inc.

FIG. 53. Amphibious operations of modern war call for landing craft which displace very little water. Medium tanks are shown here, trundling down the ramp and ashore from an LST (landing ship, tanks) during maneuvers. The shallow draught of these ships makes it possible to land on almost any beach, without need of a dock. They helped to make possible the United Nations' invasion of Europe on D-Day, June 6, 1944.

law of flotation. It adds but little to the weight of the wearer, but it increases his volume very greatly; hence the combination displaces more water. The various methods of finding the density of solids and liquids depend upon Archimedes' principle. The various types of buoys are examples of the principle of flotation. The supply of gasoline to an engine by means of a carburetor is controlled by a floating device, and a floating ball closes the valve which shuts off the water supply in the tank of the lavatory.

## QUESTIONS

1. Do you think that you could float in a tank of gasoline? Give a reason for your answer.

2. Explain how a battleship, which is covered with steel plates from 10 to 18 in. thick, can float on water.

3. Given a flatboat. Explain how you could use this boat to find the weight of a locomotive.

4. Does a boat rise or sink deeper as it goes from fresh water into salt water? Explain.

5. In general, what fractional part of a floating body is submerged as it floats in water?

6. Would a solid iron ship float in mercury?

7. How do boatbuilders utilize Archimedes' principle and the laws of flotation?

8. What principle is involved in the use of the floating buoy?

9. What do we mean when we say that the displacement of a vessel is 30,000 tons?

10. By deep breathing an adult can inhale about a gallon of air. Explain how this fact affects his ability to float in water.

11. When eggs begin to decompose, gases accumulate within the shell. How could you use a salt-water solution to test the freshness of eggs?

12. In pulling up an anchor, why does it seem so much heavier just as it is being lifted above the surface of the water?

13. How does the fisherman who ties both a piece of cork and a piece of lead to his line utilize the laws of flotation?

14. Occasionally a newly buried steel fuel-oil tank rises to the surface of the ground after a heavy rain. Explain.

15. Do you think that it is easier for a person to swim in water 10 ft. deep than in water 6 ft. deep? Explain.

16. If you wish to float easily, how much of your body should be submerged?

## PROBLEMS

### Group A

1. A cubical block of wood 10 cm. on a side floats in water. Its density is 0.8 gm. per c.c. Find, (*a*) the volume of the block; (*b*) its weight; (*c*) what fractional part of the block is submerged as it floats; (*d*) what force is needed to sink the block.

2. A stick 10 in. long sinks to a depth of 7 in. in water. Find its density.

3. How deep does the stick of Problem 2 sink in gasoline which has a density of 0.72 gm./c.c.?

4. How deep does the stick of Problem 2 sink in chloroform whose density is 1.5 gm./c.c.?

5. A person displaces exactly 2.5 cu. ft. of sea water. What is his volume? What is his weight in air? What is his apparent weight in sea water?

6. A flatboat is 30 ft. long, and 24 ft. wide. How heavy is the load which will cause it to sink 2 ft. deeper in sea water?

7. A canoe weighs 90 lb. How many cu. ft. of water must it displace if it is to carry 2 persons weighing 160 lb. each?

8. A scow 30 ft. long and 15 ft. wide floats in sea water. A man marks the water line on the side of the scow. Then he adds to the scow 6 cu. yd. of sand, density 150 lb./cu. ft. How much higher will the new water line be after the sand is added?

9. A cube of iron 10 cm. on a side weighs 7600 gm. in air. What will it weigh in water? What will it weigh in gasoline, density 0.7 gm. per c.c.? What will be its apparent weight in mercury, density 13.6 gm./c.c.?

### Group B

10. A block of wood 4 ft. long × 2 ft. wide × 15 in. thick is floating in sea water. What is its volume? If it weighs 508 lb. in air, what is its density? What force must be applied to it to submerge it?

11. A block of ice 10 ft. long × 8 ft. wide × 2 ft. thick floats with 0.9 of its volume submerged in sea water. Calculate its weight and also the force which must be applied to sink it.

12. A floating dry dock has 8 compartments (Fig. 54), each 12 ft. × 12 ft. × 1000 ft. long. How heavy a vessel can this dry dock float?

13. The head of a hammer weighs 1520 gm.; its density is 7.6 gm./c.c. The handle has a volume of 2000 c.c., and a density of 0.7 gm./c.c. If the combination is thrown into water, what volume will it displace? What force is needed to keep it from sinking?

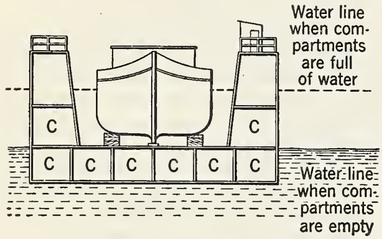

Water line when compartments are full of water
C
C
C
C
C
C
C
C
Water line when compartments are empty

Fig. 54. A floating dry dock.

14. If the hammer described in Problem 13 is thrown into a liquid whose density is 1.4 gm./c.c., will it sink or float? What force is required to keep it from sinking or floating?

15. A cubical block 20 cm. on a side is submerged in water until its upper surface is just 20 cm. below the water surface and parallel to it. Find the total downward force of the water upon the block. Find the buoyant force on its lower surface.

16. If the block of Problem 15 is submerged to such a depth that its upper surface is exactly 40 cm. beneath the water surface, what is the downward force upon the block? Has the block lost more weight in water than in Problem 15?

17. How much force would it take to sink a slab of balsa wood 6 ft. long, 18 in. wide, and 6 in. thick in sea water, if its density is 7.5 lb./cu. ft.? Could you stand on the block with safety?

18. How many cu. in. of lead, density 705 lb./cu. ft., will be needed to submerge the block of balsa wood of Problem 17, if the lead is placed upon the top of the slab? How many cu. in. of lead will be needed to sink the block if the lead is attached to the lower surface of the block?

## 4. Density and Specific Weight

**51. What are density and specific weight?** Several times we have had occasion to mention the density of a substance. Sometimes it is an advantage to compare the density of one substance with that of another. For such a purpose, we need a standard. *Water is the standard* which physicists have chosen with which to compare the densities of all solids and liquids. For gases, *air* or *hydrogen* is used as the standard. In physics, we use the word *specific* to imply a ratio. Hence, *the weight of a substance compared to the weight of an equal volume of the standard,* such as water or air, *is called its specific weight.* Since we merely compare the density of a substance with the density of water, we might use the term *specific density.* The term *specific gravity* is often used, but beginners seem to understand more easily the terms *specific weight* or *specific density.*

We find by experiment that 1 c.c. of copper weighs 8.8 gm. We know from the definition that 1 c.c. of water weighs 1 gm. In the metric system, the density of copper is 8.8 gm./c.c. and the density of water is 1 gm./c.c. Hence, copper is 8.8 times as dense as water. The *abstract number*, 8.8, which tells how many times as dense or "how many times as heavy" copper is as water is called the specific density or the specific weight of copper. The density of copper is a *concrete* number, 8.8 gm./c.c. The specific weight or *specific* density is an *abstract* number, 8.8. Numerically, they are the same in the metric system.

If we weigh 1 cu. ft. of copper, we find that it weighs 549.12 lb. One cu. ft. of water weighs 62.4 lb. By dividing 549.12 by 62.4 we get the abstract number 8.8. Of course the equal volumes of copper and water will have the same relative weights, whether they are both weighed in tons, pounds, ounces, or grams. In Appendix B you will find tables showing the specific weights of several substances. To find the density of any substance from the table, we *multiply 1 gm. by its specific weight* if we use the metric system, or *62.4 lb. by its specific weight* if we use the English system.

**52. How can we find specific weight?** We can find the specific weight of a substance experimentally by finding its density and dividing that number by the density of water. It is always true that:

$$\text{Sp. wt.} = \frac{\text{density of } x \text{ substance}}{\text{density of water}}.$$

Possibly it is easier to use a slightly different statement and then proceed to explain how each term can be found experimentally:

$$\text{Sp. wt.} = \frac{\text{wt. of } x \text{ substance}}{\text{wt. of same volume of water}}.$$

By the use of Archimedes' principle we can easily find the *weight of the same volume of water,* since a body submerged in water loses as much weight as the weight of the water displaced. In general, then, we proceed as follows when we wish to find the specific weight of any body: (*a*) we weigh the body to find its weight in air; (*b*) we find the weight of an equal volume of water by finding how much weight the body loses when submerged in water; (*c*) we divide the weight of the body by the weight of the same volume of water.

**53. How can we find the specific weight of solids?** 1. *Solids heavier than water.* If the solid is insoluble, we first weigh it in air and then weigh it in water. The *difference* between the two weights is the loss of weight in water, or the weight of the same volume of water. Then,

$$\text{Sp. wt.} = \frac{\text{weight in air}}{\text{loss of weight in water}}.$$

PROBLEM. A stone weighs 30 gm. in air, and 20 gm. in water. Find its specific weight.

*Solution.* Loss of weight in water is 10 gm. Then, 30 gm. ÷ 10 gm. = 3, the sp. wt. The volume of the stone must have been 10 c.c., since 1 c.c. of water weighs 1 gm.

★2. *Solids lighter than water.* Since a floating object loses all its weight in water, or seems to, it is more difficult than with heavy solids to find its volume, or "the weight of the same volume of water." It is possible to use a sinker. If we find the buoyant effect on the *sinker alone,* and then the buoyant effect upon the *light solid with sinker attached,* the difference is the buoyant effect on the *light solid alone.* We proceed as follows:

1. We weigh the solid in air and call its weight $w$.
2. We find combined weight, solid

in air and sinker in water, calling the sum $w'$. (See Fig. 55.)

3. We then find the combined weight of both in water, calling this weight $w''$.

The difference between $w'$ and $w''$ is equal to the volume of the light solid, since it represents the buoyant force on the solid alone, or the weight of an equal volume of water. Hence the formula:

$$\text{Sp. wt.} = \frac{w}{w' - w''}.$$

PROBLEM. A piece of cork weighs 50 gm. A sinker immersed in water weighs 210 gm. The combined weight of the cork and sinker when submerged is 10 gm. Find the sp. wt. of the cork.

*Solution.* Sp. wt. $= \frac{w}{w' - w''}$. The weight of an equal volume of water is found by subtracting 10, the weight of both when submerged, from 260, the combined weight of cork in air and sinker in water. Then $50 \div 250 = 0.2$, sp. wt. of cork.

**54. How can we find the specific weight of liquids?** There are several methods for comparing the weight of a liquid with that of an equal volume of water. A few are given here, and another in the *Laboratory Exercises* designed to accompany this book:

1. *The bottle method.* A small flask or bottle, like that shown in Fig. 56, is first weighed. Then it is filled with water and again weighed. Next it is filled with the liquid of $x$ specific weight and weighed a third time. By subtracting the weight of the empty bottle from each of the latter weighings, we find the weight of water that the bottle can hold and the weight of the liquid of unknown specific weight that it can hold. Then,

$$\text{Sp. wt.} = \frac{\text{weight of } x \text{ liquid}}{\text{weight of water}}.$$

The bottle shown in the figure is called a *pycnometer*. Since its stopper is made of ground glass, it fits perfectly. The tiny hole through the stopper makes it easy to fill the pycnometer with exactly the same volume of liquid each time.

EXAMPLE. A small bottle weighs 22 gm.; filled with water it weighs 72 gm.; filled with alcohol it weighs 62 gm. Find the specific weight of the alcohol.

*Solution.* The bottle holds 50 gm. of water. It holds 40 gm. of alcohol. The specific weight of alcohol equals $\frac{40}{50}$, or 0.8.

2. *Loss-of-weight method* or *bulb method.* The denser a liquid, the greater its buoyancy. Hence we can find the relative weights of two liquids by comparing their buoyant effects upon some solid. A glass bulb or a platinum ball is most often used. First *we weigh the bulb in air, then in water, and then in the liquid of x specific weight.* Of course the

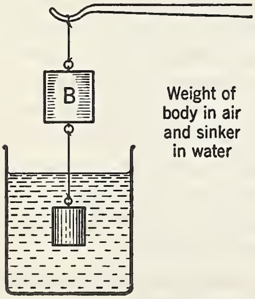


FIG. 55. Specific weight of bodies lighter than water.

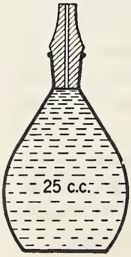


FIG. 56. A pycnometer can be filled with great precision.

bulb will displace the same volume of each liquid. If it loses twice as much weight in the $x$ liquid as in water, then the $x$ liquid must be twice as dense as water. In general,

$$\text{Sp. wt.} = \frac{\text{loss of weight in } x \text{ liquid}}{\text{loss of weight in water}}.$$

Example. A ball weighs 40 gm. in air, 32 gm. in water, and 28 gm. in a liquid of unknown density. Find the specific weight of the liquid.

*Solution.* Loss of weight in $x$ liquid is 12 gm.; the loss of weight in water is 8 gm. The buoyancy of the $x$ liquid compared with the buoyancy of water is $\frac{12}{8}$ or 1.5. Therefore the specific weight of the liquid is 1.5.

3. *The hydrometer method.* A wooden rod, loaded at one end so that it will float vertically, sinks in water until the weight of the water it displaces exactly equals its own weight. Placed in a liquid of unknown specific weight it sinks until the weight of $x$ liquid displaced equals its own weight. If the rod is uniform, the relative volumes of liquids displaced will be proportional to the depths to which the rod sinks. For example, if the rod sinks 10 cm. in water, and to a depth of 8 cm. in $x$ liquid, then $x$ liquid is $\frac{10}{8}$, or 1.25 times as dense as water.

$$\text{Sp. wt.} = \frac{\text{depth rod sinks in water}}{\text{depth rod sinks in } x \text{ liquid}}.$$

The *commercial hydrometer*, Fig. 57, has a scale so graduated that the specific weight of the liquid in which it floats may be read directly. The upper bulb is designed to increase the volume of the hydrometer, while the lower bulb is filled with shot or mercury so that the vertical position of the hydrometer will be maintained as it floats. Hydrometers may be made for use with liquids less dense than water, or for those more dense than water. It is possible to have a hydrometer for use with either type of liquid.

**55. Knowing specific weight is important.** If the story of Hiero's crown is correct, probably Archimedes was the first man who made practical use of specific weight. We use specific weight determinations to help us identify rocks and minerals. Naturally, too, men are interested in alloys that are light and strong for use in airplane parts. We may use specific-weight determinations in helping to judge the purity of substances. This is particularly true of liquids. For example, we have special hydrometers that are used to tell us when our storage battery needs recharging. A fully charged battery has a higher specific weight than one that has lost most of its charge. Some special hydrometers, called *acidimeters*, find use in testing the *concentration* of acids. The *alcoholometer* is a special hydrometer for measuring the per cent of alcohol in a

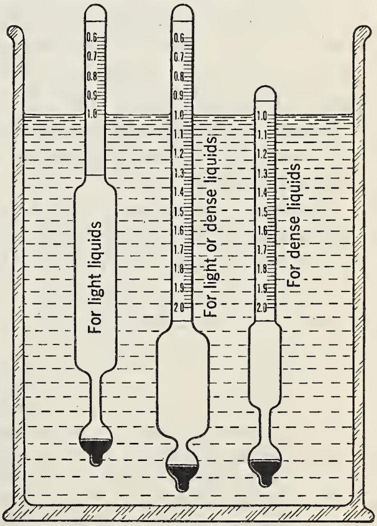


Fig. 57. Hydrometers of different types.

mixture of alcohol and water. A special hydrometer, called a *lactometer*, is used to indicate whether water has been added to milk. Milk is slightly more dense than water, having a specific weight of about 1.029. A filling station attendant estimates the freezing point of the mixture of alcohol and water in your automobile radiator by using a special hydrometer to check the specific weight of the antifreeze mixture. A low density indicates a low freezing point.

## Summary

Liquids have weight; therefore they exert pressure on the bottom and sides of the containing vessel. Liquid pressure is directly proportional to the depth and density of the liquid; it is independent of direction.

The total force exerted upon any surface by a liquid equals the product of the area times the average depth times the density.

Pressure applied to any part of a confined fluid is transmitted so as to act with undiminished force in every direction. Such pressure acts with equal force upon equal areas. This principle is known as Pascal's law.

Pascal's law finds application in the hydraulic press and in various other devices. By sacrificing speed, a small force may be used to overcome a very great resistance. In all frictionless machines, acting force times the distance the acting force moves equals resisting force times the distance the resisting force moves.

The upward force a fluid exerts on a submerged body is called its buoyancy. Archimedes found that the magnitude of this buoyant force just equals the weight of the fluid displaced.

The buoyant force on a solid immersed in water must be *greater than* its weight, exactly *equal to* its weight, or *less than* its weight. In the first case, the solid will rise to the surface and float with a part of its volume submerged. In the second case, it remains in equilibrium in the liquid; and in the third case, it sinks.

Density is the weight per unit volume. Specific weight is the weight of a certain volume of substance divided by the weight of the same volume of water.

Specific weight is found by dividing the weight of a body by the weight of a volume of water exactly equal to the volume of the body. The latter is numerically equal to the loss of weight of the body in water.

*How many of the following terms can you define or explain from memory?* (*A scientist checks his results.*)

Force
Pressure
Density
Direct proportion
Inverse proportion
Manometer
Artesian well
Pascal
Mechanical advantage
Effort
Resistance
Archimedes
Buoyancy
Displace
Alloy
Flotation
Equilibrium
Specific weight
Specific gravity
Pycnometer
Hydrometer
Acidimeter
Alcoholometer
Lactometer
Total force
Hydraulic press
Bulb method

## QUESTIONS

1. Some hydrometers are made for use with liquids lighter than water. Would you expect the upper bulb on such a hydrometer to be relatively large or rather small? Explain.

2. What is the purpose of the lower bulb of a hydrometer?

3. Some hydrometers are made for use with liquids denser than water. What would you suggest concerning their construction?

4. Some hydrometers are made for use in either light liquids or in heavy liquids. Make a sketch diagram to show how they are constructed and graduated.

5. Denatured alcohol mixed with water is used in automobile radiators in winter. The larger the per cent of alcohol, the lower the freezing point of the mixture. How can a hydrometer be used to test the freezing point of such a mixture?

6. Liquid air is a mixture of liquid nitrogen and liquid oxygen. Try to find out how glass beads of varying densities are used to find out the boiling point of the mixture and the per cent of each element present.

7. Suppose that you were handed a crown and asked to find out whether it was made of pure gold. Without destroying the crown, just how would you proceed?

8. A cube of iron loses 100 gm. when submerged to a depth of 1 m. How much will it lose when submerged to a depth of 100 m.?

9. Which do you think will have the higher specific weight, "whole milk" or "skim milk"? Give a reason for your answer.

10. Which has the higher specific weight, a heavy cream or a light cream? Explain.

11. Milk from the Jersey breed of cows has a higher per cent of butter fat than milk from some other breeds. How would you expect the lactometer reading to be affected by the high per cent of fat?

12. Why are density and specific weight the same numerically in the metric system?

13. Why are density and specific weight different numerically in the English system?

14. Make a list of as many uses as you can for the hydrometer.

## PROBLEMS

(*See the table of specific weights in Appendix B.*)

### Group A

1. A block of iron weighs 50 gm. in air, and 43.5 gm. in water. Find its sp. wt.

2. A block of aluminum weighs 50 gm. in air, and 31.5 gm. in water. Calculate the sp. wt. of aluminum.

3. Explain why 50 gm. of aluminum lose nearly 3 times as much weight in water as 50 gm. of iron.

4. What is the meaning of the expression, "The specific weight of tungsten is 18.7"? What will 10 c.c. of tungsten weigh in air? What will be the weight of 10 c.c. of tungsten in water? What will 10 c.c. of tungsten weigh in gasoline, sp. wt. = 0.7?

5. What will be the weight of 1 cu. ft. of tungsten?

6. How much weight will 50 c.c. of platinum lose in water? How much weight will 50 c.c. of magnesium lose in water?

7. How much weight will 50 gm. of platinum lose in water? How much weight will 50 gm. of magnesium lose in water?

8. A body weighs 500 lb. in air and 400 lb. in water. Find its sp. wt. Calculate its volume. What is its density?

9. A small flask weighs 35 gm. Filled with water, it weighs 135 gm. Filled with salt water it weighs 150 gm. It weighs 105 gm. when filled with gasoline. Calculate: (*a*) sp. wt. of the salt water; (*b*) sp. wt. of the gasoline.

10. A flask weighs 30 gm. Filled with water, it weighs 55 gm.; filled with chloroform, it weighs 67.5 gm.; and filled with glycerine, it weighs 61.5 gm. Find (*a*) the volume of the flask; (*b*) the sp. wt. of chloroform; (*c*) the sp. wt. of glycerine.

11. A glass bulb weighs 60 gm. in air, 30 gm. in water, and 18 gm. in nitric acid. Find (*a*) the volume of the bulb; (*b*) the sp. wt. of the bulb; and, (*c*) the sp. wt. of nitric acid.

12. A glass stopper weighs 80 gm. in air, 40 gm. in water, and 52 gm. in a liquid of unknown sp. wt. Calculate the sp. wt. of the liquid.

13. A wooden rod 15 in. long sinks in water to a depth of 11 in. Find the sp. wt. of the wooden rod. The same rod sinks in oil to a depth of 12 in. What is the sp. wt. of the oil? To what depth will the rod sink in chloroform?

## Group B

14. A block of wood weighs 80 gm. in air; a sinker weighs 200 gm. in water; the combined weight of wood and sinker in water is 170 gm. Calculate the sp. wt. of the wooden block.

15. A block of paraffin weighs 100 gm. in air. The block in air and a sinker in water have a combined weight of 340 gm. Both combined have a weight of 220 gm. in water. Find the sp. wt. of the paraffin.

16. A piece of balsa wood weighs 40 gm. in air. A sinker weighs 400 gm. in water. Both together in water have a weight of 107 gm. Find the sp. wt. of the balsa wood.

17. A block of wood weighs 80 gm. in air. When attached to a sinker which weighs 30 gm. in water, the combination has zero weight in water. Calculate its sp. wt.

18. A body weighs 60 gm. in air; its apparent weight in water is zero. Find its sp. wt.

19. What is the sp. wt. of a body that loses just half its weight in water?

20. What is the sp. wt. of a body that floats in water with exactly half its volume submerged?

21. Mercury has a sp. wt. of 13.6. What fractional part of a block of lead will be submerged as it floats in mercury?

22. What fractional part of an iceberg, sp. wt. = 0.92, floats above the surface in sea water, sp. wt. = 1.026?

23. A boy can lift 150 lb. If a stone has a sp. wt. of 3, how many cu. ft. of stone can he lift? How many cu. ft. of stone can he lift to the surface of a pond?

24. A barge 120 ft. long is 30 ft. wide. When empty its top surface rises 5 ft. above the surface of the sea water in which it floats. How many tons will be needed to sink the barge just to its top surface?

25. A box 6 ft. long × 5 ft. wide × 4 ft. deep is filled with water. Calculate the weight of water in the box. Calculate the pressure on the bottom and also the total force. If the box is covered and then stood on end, will there be any change in the weight, the total force on the bottom, or the pressure on the bottom? Calculate instead of guessing.

26. A scow is 100 ft. long and 30 ft. wide, and its bottom surface is 10 ft. below the water surface of a lake. Calculate the upward pressure on the scow and the total upward force. Calculate the volume of the water displaced and the tonnage displacement of the scow.

27. A cylinder loses 132 gm. in water. Calculate (*a*) its volume; (*b*) its weight in air; (*c*) its weight in carbon tetrachloride, sp. wt. = 1.6; the sp. wt. of the cylinder is 8.8.

28. An anchor of cast iron loses 192 lb. in sea water. What is the volume of the anchor and its weight in air?

29. It is estimated that some stars are so dense that 1 cu. in. weighs 1 ton. Calculate the sp. wt., water standard.

# *Mechanics of Gases*

## 1. The Atmosphere

**56. Does air have weight?** The expression "light as air" is used so frequently that one is likely to get the idea that air has no weight, or that its weight is negligible. We speak of an empty bottle, when in reality the bottle is full of air. It is actually possible to weigh air and find that its weight is appreciable.

Fig. 58 shows a glass bulb fitted with a stopcock. Let us weigh the bulb, pump the air from it, and then weigh it again. Its weight will be less than before. If we open the stopcock again, the air will rush in, and the bulb will weigh as much as it did at first. This experiment proves that air takes up room and that it can be weighed. It can be pumped from one vessel into another, just as we inflate automobile tires or exhaust vacuum bulbs. Experiments show that *one liter of air at a temperature of 0° C. and under a pressure of 76 centimeters of mercury weighs 1.293 gm.* (See Section 70.) One liter of air is about 1/773 as heavy as one liter of water.

Though air is only a fractional part as dense as water, yet the weight of air in a large room is considerable. At sea level 1 cu. ft. of air weighs a trifle more than 1.25 oz., and 1 cu. yd. a little more than 2 lb. The air in a schoolroom 30 ft. long × 24 ft. wide, with a 14-ft. ceiling, weighs nearly 750 lb.

Air is the *popular standard* for determining the specific weight of gases, although hydrogen, the lightest gas known, is often used by scientists as the standard. When hydrogen is used as the standard, there can be no specific weights of gases that are less than one. Several gases are lighter than air, including nitrogen, ammonia, and carbon monoxide, but many gases are considerably denser than air.

**57. Does air exert pressure?** We move about in the air so easily that we are unconscious of its weight or pressure. Since air has weight, it must exert pressure. If we go down into a deep mine or up in an elevator, our eardrums make us conscious of the fact that the air pressure changes with varying altitudes.

Suppose that we tie a thin rubber membrane over a bladder glass, as in Fig. 59, and then pump the air out of the glass. The rubber is pressed farther and farther down into the glass as we

---

### Vocabulary

Aneroid, without liquid.

Caisson, a watertight chamber used for construction work under water.

Dehydrate, to remove water from a food or other substance.

Pneumatics, that branch of physics that deals with the mechanical properties of gases.

Unbalanced, applied to a greater force on one side of an object than exists on the opposite side.

gradually pump out the air, and the membrane will probably burst. As we exhaust the air from the inside, we remove the *upward pressure* which the air inside had been exerting, and the *unbalanced downward pressure* causes the membrane to burst.

We may also use an empty varnish can to show air pressure. Let us take a can of one-half gallon capacity, put into it a little water, and then heat the water to boiling. The steam that forms drives all the air out of the can. Next let us stopper the can tightly and cool it by holding it under running water. As the steam condenses and produces a vacuum inside, the unbalanced outside pressure crushes the can. Common sense tells us that if air has weight, it must exert pressure.

Like liquids, gases are fluid, although they are more mobile; their elasticity is almost perfect. Therefore, the facts we have already learned concerning liquid pressure and the principle of Archimedes apply to gases as well as to liquids.

Although we really live at the bottom of an "ocean of air," we do not feel the pressure which the atmosphere exerts, because the pressure is nearly equal in all directions. When we see the wind breaking the limbs of trees, uprooting trees bodily, or toppling over buildings, then we begin to realize the enormous pressure which the air can exert.

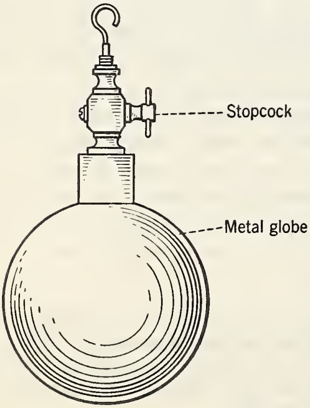


FIG. 58. A baroscope globe.

**58. Why do liquids rise in exhausted tubes?** Every time we suck soda water through a straw we demonstrate the fact that liquids rise in exhausted tubes. The Greeks and Romans explained this phenomenon by saying that "Nature abhors a vacuum," — the liquid rising to take the place of the air which is removed by suction. Just how absurd this idea is may be pictured if we try to imagine nothing (a vacuum) pulling something up the tube.

About the middle of the 17th century the Duke of Tuscany had a well dug, but he found that the water would not rise more than 32 ft. in the tube of the pump he was using. Then he went to Galileo for an explanation. The aged philosopher answered, "Evidently nature's horror of a vacuum does not extend beyond 32 feet."

Whether Galileo knew the correct reason is uncertain. He did know that

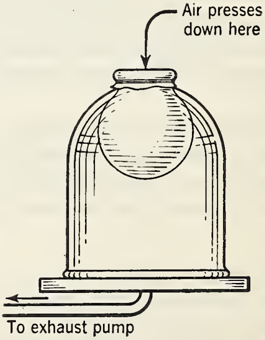


FIG. 59. Air presses membrane down into bell jar.

air has weight and probably suspected that it was the pressure of the atmosphere that pushed liquids up exhausted tubes. (See Fig. 60.) He devised an experiment to explain this phenomenon, but his death in 1642 occurred before he had time to carry it out. Torricelli, his brilliant pupil, continued the experiment which explains conclusively why liquids rise in exhausted tubes.

**59. What was Torricelli's experiment?** Torricelli suspected that it was the pressure of the surrounding air that *pushed* the water up the tube of the Duke of Tuscany's pump. Hence he reasoned that mercury, which is 13.6 times as dense as water, would be pushed up only 1/13.6 times as far in an exhausted tube. He took a glass tube about 3 ft. long, closed at one end, and filled it with mercury. Placing his finger over the open end of the tube, he then inverted it in a bowl of mercury. (See Fig. 61.) When he removed his finger from the opening, only a little of the mercury flowed out of the tube. The mercury column, *AB*, stood at a height of about 30 in. above the level of the mercury in the bowl. Thus Torricelli proved that the atmospheric pressure at sea level is just counterbalanced by a column of mercury 30 in. high. It is not strictly correct to say that liquids "rise" in exhausted tubes; they are "pushed up" the tube by the pressure of the air on the surface of the liquid outside the tube.

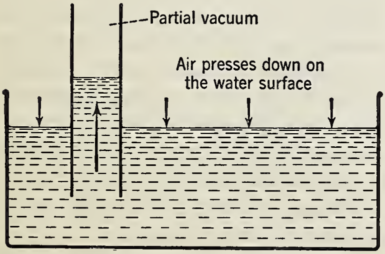


FIG. 60. Liquids are pushed up into exhausted tubes by air pressure.

**60. Pascal convinced himself.** When Pascal learned of Torricelli's experiment, he was not entirely convinced that his explanation was correct. He reasoned that if the mercury column in a Torricellian tube was actually sustained by the pressure of the atmosphere, the height at which such a column stands would be less at higher altitudes than at sea level. He carried a Torricellian apparatus to the top of a tower in Paris and found a slight decrease in the height of the mercury column. Then he wrote to his brother-in-law, requesting him to repeat the experiment by carrying a Torricellian apparatus to the top of Puy-de-Dôme, a mountain about 1000 meters high. The mercury fell about 8 cm. in the tube as he made the ascent, and he wrote to Pascal that he was "ravished with admiration and astonishment." We know that water pressure increases with the depth. Since the atmosphere is an "ocean of air," we are not sur-

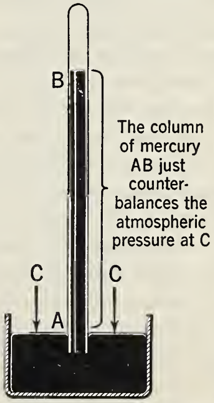

B
The column of mercury AB just counterbalances the atmospheric pressure at C
C
C
A

FIG. 61. A Torricellian apparatus.

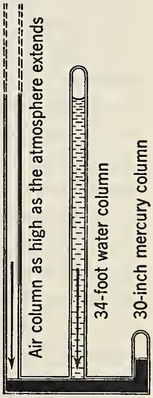


FIG. 62. All these pressures are equal.

FIG. 63. Blaise Pascal (1623–1662) was a French philosopher. In mathematics he wrote a treatise on conic sections. The pupil in physics will remember Pascal for his experiments on liquid pressure and his researches with a Torricellian apparatus.

prised that the pressure in the valleys is greater than it is on the mountain tops. There is this difference, however: air is so compressible that its density varies with the altitude, while the density of water is not much affected by the depth. (See Fig. 63.)

**61. How great is the atmospheric pressure?** The experiments begun by Torricelli and elaborated by Pascal prove conclusively that the height to which a liquid will rise in an exhausted tube depends upon the pressure of the air on the surface of the liquid outside the tube. The average of a large number of experiments shows that the air at sea level exerts sufficient pressure to counterbalance a mercury column 76 cm. high (about 30 in.). Since we know how to calculate fluid pressures, we can find the magnitude of the pressure which the air exerts. Since pressure equals depth times density, we multiply 76 cm. by 13.6 gm./c.c. Thus we find that the air pressure is 1033.6 gm. on every square centimeter of surface at sea level.

In the English system, 30 in. = 2.5 ft., the depth. The density of mercury = 62.4 × 13.6 (its sp. wt.), or 848.6 lb./cu. ft. Then,

$$p = \frac{2.5 \text{ ft.} \times 848.6 \text{ lb./cu. ft.}}{144}.$$

The pressure is 14.7 lb. per sq. in., which is known as the "pressure of one atmosphere." "Two atmospheres pressure" would equal 29.4 lb. per sq. in.

If we made a Torricellian tube to be filled with water, it would need to be 13.6 × 30 in., or 34 ft. long. If the atmosphere exerts only enough pressure at sea level to raise a column of water 34 ft., we can readily understand why the Duke of Tuscany's pump would not lift water more than 32 ft., because no pump can produce a perfect vacuum. The Torricellian vacuum is nearly perfect. Fig. 62 shows three tubes which represent the relative pressures of mercury, water, and the atmosphere.

**62. The Magdeburg hemispheres.** In 1650 Otto von Guericke, Mayor of Magdeburg, conceived the idea that air, which he believed to be a substance, could be pumped out of a container. In that year he invented the *air pump*, or *vacuum pump*, probably being at the time entirely ignorant of the work of Torricelli and Pascal. He was anxious to learn whether any peculiar effects could be observed in the space, or vacuum, from which the air had been exhausted.

Incidentally, he devised a striking experiment which helps to give us an

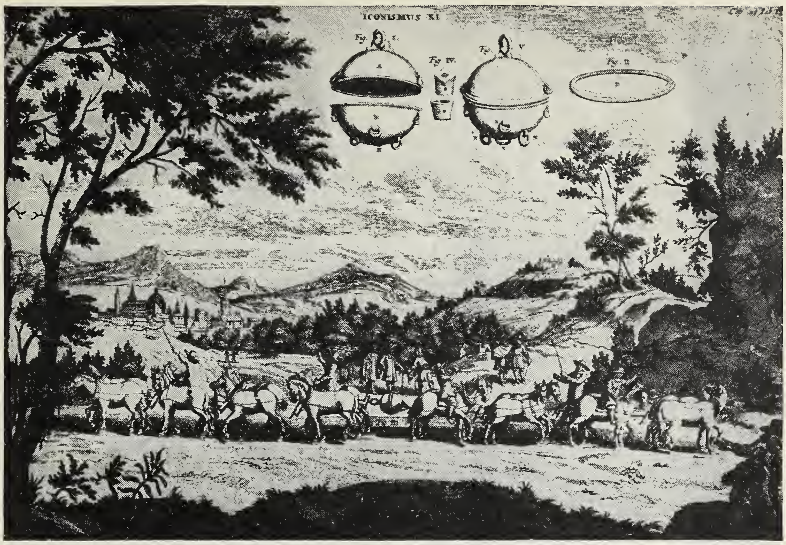


FIG. 64. Otto von Guericke's experiment as performed at Magdeburg.

idea of the enormous pressure of the outside air upon a vessel from which the air has been pumped. He made two hollow hemispheres, about 22 in. in diameter. The edges were ground so smooth that when covered with a heavy grease and placed together they fitted airtight. He then pumped the air out of the hemispheres and closed the stopcock. In a demonstration held in the presence of the Emperor and the Reichstag, it is said to have required 16 horses, eight on each side, to pull the hemispheres apart. (See Fig. 64.) Small hemispheres of this type are found in every physics laboratory. Although they are usually only 3 or 4 in. in diameter, two strong boys cannot pull them apart when they are fitted airtight and evacuated.

**63. The mercurial barometer.** A barometer is used to *measure* the pressure of the air at any given place or time. If we have a Torricellian tube and bowl, it is a simple matter to make a barometer. We need a support for the tube and a measuring stick to find the height of the mercury column. Sometimes the tube is attached to a board upon which a scale is marked; in other cases a measuring stick is fastened to the board alongside the tube. Quite often a metal tube is used as a frame to support the tube and bowl, and to protect them against breakage. (See Fig. 65.) The scale in inches or centimeters is etched on the metal tube. Such a tube has a vertical slot cut in it near the top so that the level of the mercury in the Torricellian tube can be seen and measured. (See Fig. 66.)

If the air pressure grows less, some of the mercury will flow out of the tube into the bowl, and conversely. This changes the level. In order to have a fixed point from which to measure the height of the column, a small pointed ivory peg is mounted on the

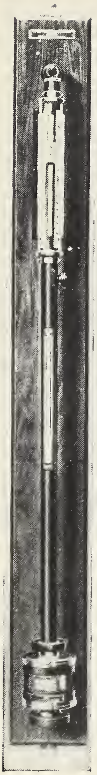


Fig. 65. Mercurial barometer.

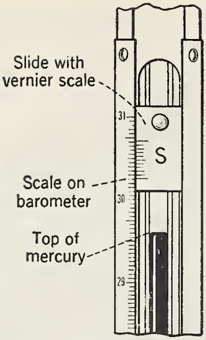


Fig. 66. A vernier scale is used to read the barometer accurately.

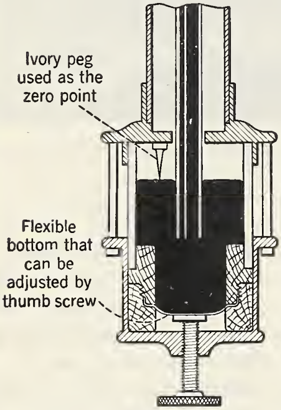

Ivory peg used as the zero point
Flexible bottom that can be adjusted by thumb screw

Fig. 67. Bowl of barometer.

frame just inside the bowl. The point of the peg is used as the zero mark of the scale. By means of a flexible membrane and a thumbscrew, as shown in Fig. 67, the surface of the mercury in the bowl can always be raised or lowered to coincide with the tip of the ivory peg, and this should always be done before any readings are taken.

Mercury is suitable for use in these cistern barometers, as they are sometimes called, because it has a high specific weight, and it does not freeze readily. It does expand, however, with an increase in temperature. Hence readings taken with a mercurial barometer must be corrected for temperature changes.

**64. The aneroid barometer.** Since the mercurial barometer described in the preceding section must be at least 3 ft. in length, it is awkward to handle. It is not easily portable, and it must hang in a vertical position. Hence such a barometer would not be satisfactory on a rolling ocean vessel, or on an airplane, especially one in which the aviator wished to loop-the-loop.

The *aneroid* (without liquid) barometer is convenient and is not affected by a change in position. It consists essentially of a shallow box, with a thin, corrugated metal cover. (See Fig. 68.) Since there is a partial vacuum in this box, the *elastic* cover is very sensitive to changes in atmospheric pressure. The base of the metal box is fastened to the base of the instrument. As the top moves up or down in response to pressure changes, its motion is communicated to a system of levers. A slight motion of the elastic cover applied to the short end of a lever is multiplied at the long end of the lever. By such multiplying devices, it becomes easy to perceive the slightest change in the diaphragm, or metal cover. The lever motion is communi-

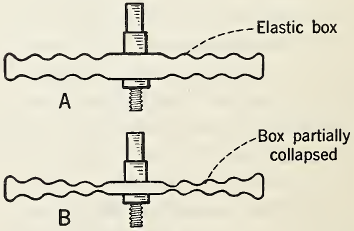


Fig. 68. The top figure shows a partially evacuated metal box. The lower figure shows how the box collapses under air pressure.

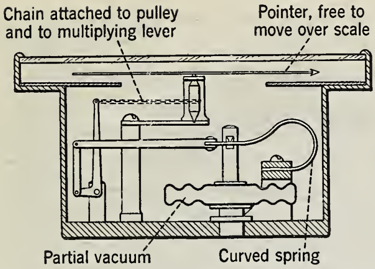

Chain attached to pulley and to multiplying lever
Pointer, free to move over scale
Partial vacuum
Curved spring

Fig. 69. Diagram to show how an aneroid barometer operates.

cated by a chain or cord to a pointer that moves over a graduated scale. (See Fig. 69.) Of course this scale must be graduated or calibrated by comparison with a standard mercurial barometer.

The aneroid barometer may be made of practically any size. Some are small enough to be carried in the pocket like a watch. Many of them are about the same size as an ordinary alarm clock. A good aneroid barometer is so sensitive that it shows a change of pressure when lowered from a table to the floor. (See Fig. 70.)

The self-recording aneroid barometer, or *barograph*, carries a long pointer which traces in ink a continuous record of the atmospheric pressure. (See Fig. 71.) Sheets of paper are marked with horizontal lines to indicate pressures, and vertical lines to show the days and hours of the week. These sheets are fastened to a cylinder which is turned by clockwork through one complete revolution in one week. As the paper turns on the cylinder, the pointer traces a continuous line that shows the pressure for any time during the week. Sheets of this kind may be filed as a permanent record of the atmospheric pressure. Fig. 72 shows such a record

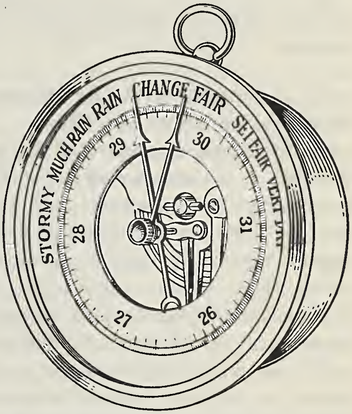


Fig. 70. An aneroid barometer. The corrugated box can be seen near the bottom of the instrument. One pointer is set and remains stationary to compare the changes in barometric pressures over given intervals.

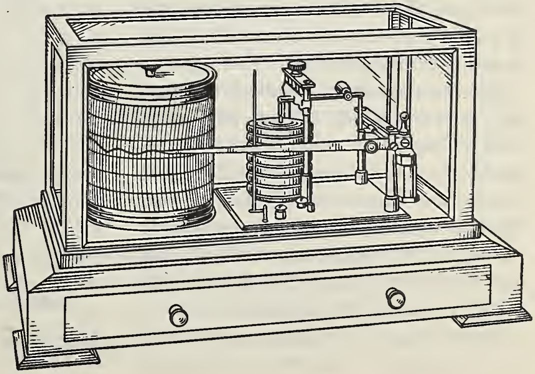


Fig. 71. Barograph. A self-recording barometer. Several collapsible metal boxes are used in this sensitive instrument. The charts may be filed to furnish a complete record of air pressures over any given periods of time. An eight-day clock turns the cylinder once around in eight days.

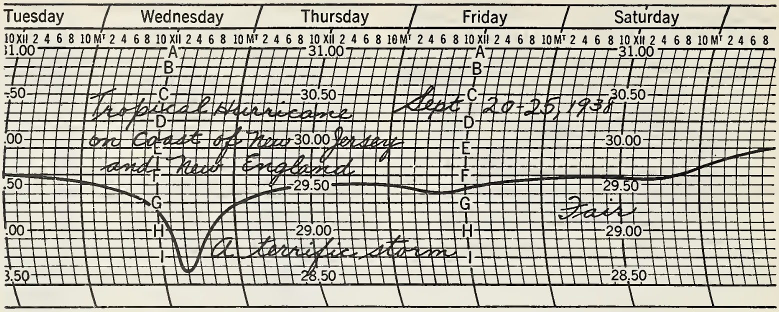


FIG. 72. Observe the sudden dip in barometric pressure during the hurricane of September, 1938. Extremely low pressures are associated with such storms as this West Indian hurricane.

made at Newark, N. J., for the week beginning September 18, 1938.

**65. What are some uses of the barometer?** 1. *To measure altitudes.* For many years the barometer has been used to measure altitudes. At the present time it is used more extensively than before, since the determination of altitudes is of so much importance to aviators and balloonists. Aneroid barometers for use on airplanes are graduated to read altitudes directly. They are called *altimeters.*

A new "terrain clearance indicator" has been designed to replace the standard altimeter. The new instrument warns the pilot of a rise in ground elevation ahead of him or to one side and also registers his clearance as he passes over an elevation.

For comparatively small elevations, the barometer falls 0.1 in. for every 90 ft. of ascent. The fall is not so regular above a few hundred feet. At the top of Mt. Blanc (15,781 ft.) the barometer reading is approximately half what it is at sea level, while at the top of Mt. Everest (29,141 ft.) the barometer reading is less than 10 in.

By putting a Torricellian apparatus in a bell glass so that the air pressure may be reduced by means of a vacuum pump, as shown in Fig. 73, we can very easily see what happens to the mercury column as we pump the air from the bell glass. Without the necessity of carrying a barometer to the top of a mountain, we can observe what happens to the mercury column in a barometer as the air pressure is lowered. By the use of the Torricellian tube supported in a bottle of mercury by means of a two-holed rubber stopper, we can easily observe the fluctuations in the height of the mercury column as we change the pressure by sucking or blowing through a rubber

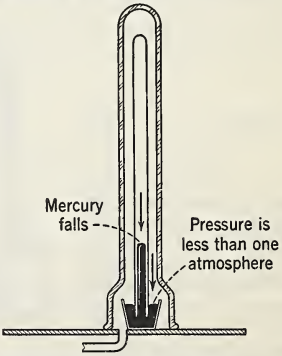


FIG. 73. Mercury falls in barometric tube as pressure is reduced.

tube attached to the other hole in the stopper.

2. *To forecast weather.* The beginner in physics is generally astonished to learn that *dry* air is denser than *moist* air. But water vapor is only about 0.6 as dense as air. Hence, the more moisture the air contains, the less pressure it exerts. For that reason the barometer falls in moist weather. This fact is just contrary to the popular belief that moist air is *heavy.* It is *oppressive,* but really less dense than dry air. Such errors often occur through our misuse of the English language. We speak of a "heavy" cream, when we mean a "thick" cream. Cream is light enough to float on milk, and "extra heavy cream" is actually less dense than "heavy cream."

A rising barometer shows that the density of the air is increasing. Hence,

*A rising barometer indicates fair or clearing weather.*

*A rapidly falling barometer indicates an approaching storm.*

*Continued high barometer indicates steady, fair weather.*

**66. How are weather maps made?** From a single reading of the barometer it is impossible to make any accurate predictions concerning weather conditions. By observing successive readings of the barometer, however, some success in forecasting may be attained. But to get results that are of real value, one must study the readings of a number of barometers scattered over a wide area. The United States Government has observers stationed at various points throughout the United States. Reports taken simultaneously are telegraphed to central stations, where weather maps are prepared as follows: On a blank map of the United States heavy lines called *isobars* are drawn through places that report the same barometric pressure. A dotted line called an *isotherm* is drawn through those places where the temperature was 32° F. at 2:30 E.W.T. (Eastern War Time) when the observation was taken. An isotherm for 0° F. may also be included. Arrows, used to show wind direction, fly with the wind. The feathers on the shaft of the arrows indicate the force of the wind on the Beaufort Scale. Precipitation is shown by shading, and the condition of the sky, whether clear, cloudy, partly cloudy, is shown by the shading within the circles that represent the tips of the arrows. Some 96 different symbols are used to represent rain, fog, snow, lightning, thundershowers, and so forth. Code figures show the height of visibility, or the ceiling, in feet and the distance at which objects are visible in yards or miles, measured horizontally. The table at the top of page 58a shows the code numbers and their values, the values of the Beaufort Scale, and the state of sky.

The isotherms run in a general east and west direction, but the isobars form open or closed curves around "high pressure areas" and "low pressure areas." Just as water flows from high pressure to low pressure, or runs down hill, so winds blow from regions of high barometric areas toward low pressure areas. In general, *winds blow toward the center of low pressure areas, but the rotation of the earth on its axis deflects the winds so that the storm has a rotary motion.* Low pressure storms are called *cyclones*, but this word does not have the same meaning as "tornado." The winds in such cyclonic storms blow in a *counter-clockwise* direction in the northern hemisphere. They generally move from west to east across the

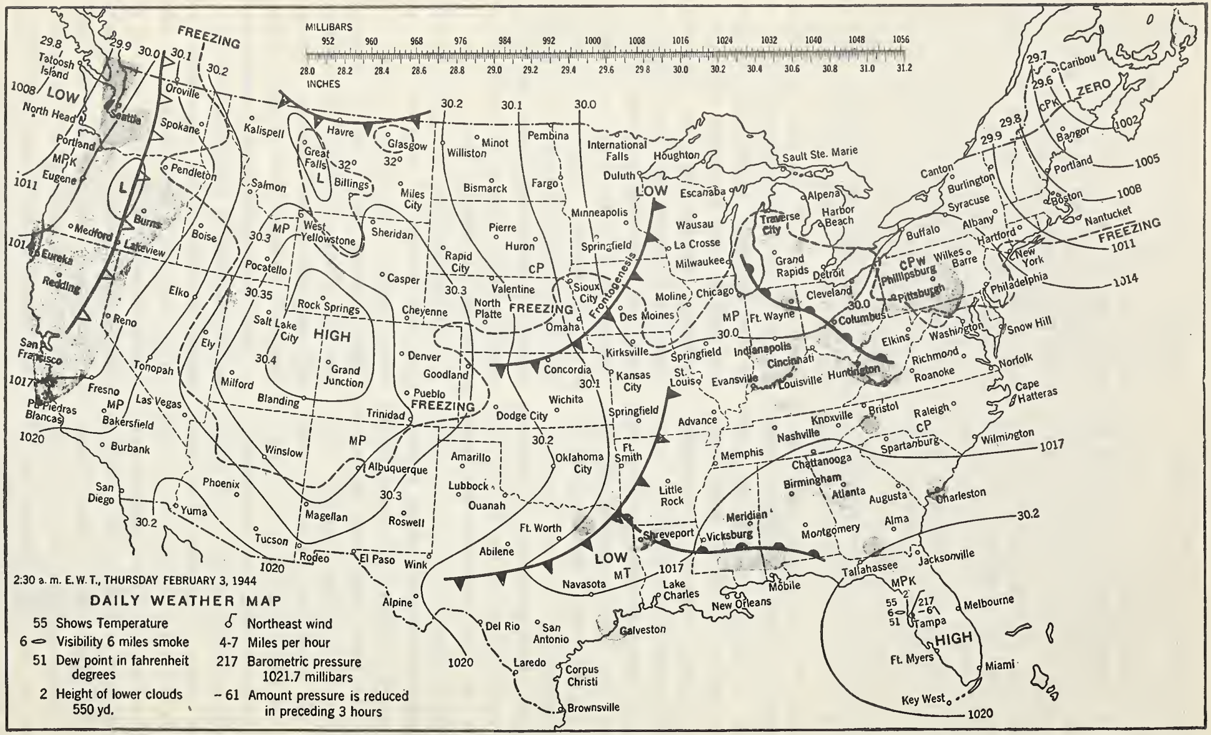

MILLIBARS
952 960 968 976 984 992 1000 1008 1016 1024 1032 1040 1048 1056
28.0 28.2 28.4 28.6 28.8 29.0 29.2 29.4 29.6 29.8 30.0 30.2 30.4 30.6 30.8 31.0 31.2
INCHES
2:30 a. m. E. W. T., THURSDAY FEBRUARY 3, 1944
DAILY WEATHER MAP
55 Shows Temperature
6 Visibility 6 miles smoke
51 Dew point in fahrenheit degrees
2 Height of lower clouds 550 yd.
Northeast wind
4-7 Miles per hour
217 Barometric pressure 1021.7 millibars
-61 Amount pressure is reduced in preceding 3 hours
FREEZING
ZERO
LOW
HIGH
Frontogenesis
MPK
MP
CP
CPK
CPW
MT
L
29.7
29.6
29.8
29.9
30.0
30.1
30.2
30.3
30.35
30.4
1002
1005
1008
1011
1014
1017
1020
32°
Tatoosh Island
North Head
Seattle
Portland
Eugene
Medford
Eureka
Redding
San Francisco
Piedras Blancas
Fresno
Bakersfield
Burbank
San Diego
Oroville
Spokane
Pendleton
Burns
Lakeview
Reno
Boise
Elko
Tonopah
Las Vegas
Yuma
Phoenix
Tucson
Rodeo
Kalispell
Salmon
Great Falls
Havre
Billings
Glasgow
Miles City
West Yellowstone
Pocatello
Salt Lake City
Ely
Milford
Blanding
Rock Springs
Grand Junction
Sheridan
Casper
Cheyenne
Denver
Pueblo
Trinidad
Winslow
Albuquerque
Magellan
Roswell
El Paso
Wink
Alpine
Williston
Minot
Bismarck
Pembina
Fargo
Pierre
Huron
Rapid City
Valentine
North Platte
Goodland
Dodge City
Amarillo
Lubbock
Ouanah
Abilene
Del Rio
San Antonio
Laredo
Corpus Christi
Brownsville
Galveston
Navasota
Ft. Worth
Oklahoma City
Wichita
Concordia
Omaha
Sioux City
Minneapolis
Springfield
International Falls
Duluth
Houghton
Escanaba
Wausau
La Crosse
Milwaukee
Des Moines
Moline
Chicago
Kirksville
Kansas City
St. Louis
Springfield
Ft. Smith
Little Rock
Shreveport
Lake Charles
New Orleans
Mobile
Vicksburg
Meridian
Memphis
Advance
Evansville
Louisville
Cincinnati
Indianapolis
Ft. Wayne
Grand Rapids
Traverse City
Sault Ste. Marie
Alpena
Harbor Beach
Detroit
Cleveland
Columbus
Huntington
Elkins
Pittsburgh
Phillipsburg
Wilkes Barre
Buffalo
Canton
Burlington
Syracuse
Albany
Hartford
New York
Philadelphia
Washington
Snow Hill
Richmond
Roanoke
Norfolk
Cape Hatteras
Raleigh
Wilmington
Knoxville
Bristol
Nashville
Chattanooga
Birmingham
Atlanta
Augusta
Spartanburg
Charleston
Montgomery
Alma
Tallahassee
Jacksonville
Tampa
Ft. Myers
Melbourne
Miami
Key West
Caribou
Bangor
Portland
Boston
Nantucket

FIG. 74. The low barometric area is associated with stormy weather. The high barometric area is associated with clear, cold weather. P and T indicate respectively air masses which are polar or tropical in origin. The letters M and C indicate respectively the maritime and continental surfaces over which the air mass formed. W shows that an air mass is warmer than the surface over which it passes; K that it is colder. Signs in left corner refer to Tampa, Florida.

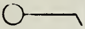
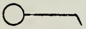
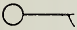
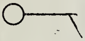
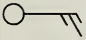
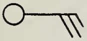
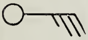
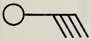
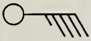
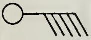
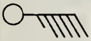
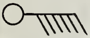
| BEAUFORT SCALE OF WIND FORCE | | | VISIBILITY SCALE (IN MILES) | | CEILING SCALE (HEIGHT, LOWER CLOUDS) | | VALUES, $N$ SYMBOLS AND $N_h$ FIGURES | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Symbol | Miles per Hour | Number | Objects Not Visible at (Highest Number Used) | Number | Height in Feet | $N$ | $N_h$ | Amount of Sky Covered by Clouds |
| 0 | | Calm | 0 | $\frac{1}{32}$ (55 yards). | 0 | 0 to 163. | | 0 | No clouds. (Figure 0 not entered on map.) |
| 1 |  | 1–3 | 1 | $\frac{1}{8}$ (220 yards). | 1 | 164 to 327. | | 1 | Less than one-tenth. |
| 2 |  | 4–7 | 2 | $\frac{5}{16}$ (550 yards). | 2 | 328 to 655. | | 2 | One-tenth. |
| 3 |  | 8–12 | 3 | $\frac{5}{8}$ (1,100 yards). | 3 | 656 to 983. | | 3 | Two- to three-tenths. |
| 4 |  | 13–18 | 4 | $1\frac{1}{4}$ (2,200 yards). | 4 | 984 to 1,967. | | 4 | Four- to six-tenths. |
| 5 |  | 19–24 | 5 | $2\frac{1}{2}$ miles. | 5 | 1,968 to 3,280. | | 5 | Seven- to eight-tenths. |
| 6 |  | 25–31 | 6 | 6 miles. | 6 | 3,281 to 4,920. | | 6 | Nine-tenths. |
| 7 |  | 32–38 | 7 | 12 miles. | 7 | 4,921 to 6,561. | | 7 | More than nine-tenths, but with openings. |
| 8 |  | 39–46 | 8 | 30 miles. | 8 | 6,562 to 8,201. | | 8 | Ten-tenths, or completely covered. |
| 9 |  | 47–54 | 9 | Unlimited. | 9 | Above 8,202. | | 9 | Sky obscured. |
| 10 |  | 55–63 | | | | | | | |
| 11 |  | 64–75 | | | | | | | |
| 12 |  | Above 75 | | | | | | | |

FIG. 75. This table shows the meanings of the various symbols that are used on United States Weather Maps.

United States. As a rule, *they are accompanied by cloudy weather, with rain, snow, or some other form of precipitation, and temperatures somewhat above normal.*

The general direction of the winds is outward from areas of high pressure, but the rotation of the earth on its axis causes them to move in a rotary direction, which is *clockwise* in the northern hemisphere. Such storms are known as anti-cyclones. They are generally *accompanied by fair or clear weather, with temperatures below normal.*

The isobars used on the older maps represented air pressure in inches of mercury, but the United States weather maps now show isobaric pressures in millibars, which are based upon absolute units. The following table shows the corresponding relation between the barometric pressure in inches and the pressure in millibars:

| Inches | Millibars | Inches | Millibars |
|---|---|---|---|
| 27 | 914 | 29.5 | 999 |
| 27.5 | 931 | 30 | 1015 |
| 28 | 948 | 30.5 | 1032 |
| 28.5 | 965 | 31 | 1049 |
| 29 | 982 | 31.5 | 1056 |

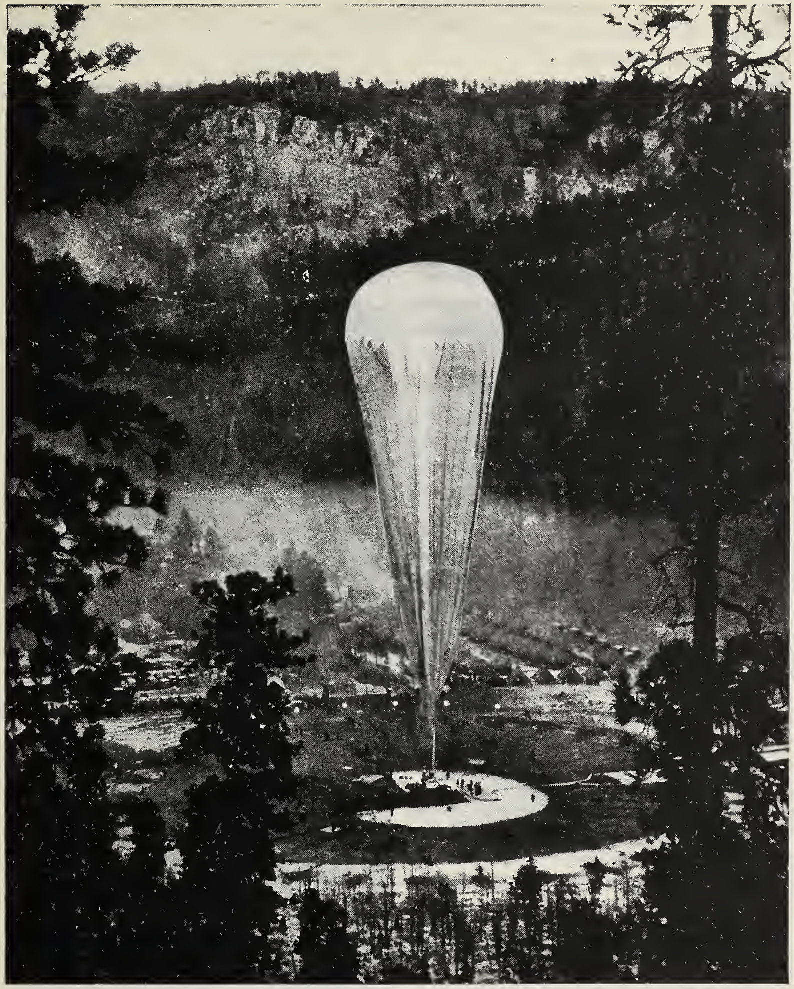
On page 58 a weather map is shown with the isobars labeled in inches at one end of the open curves and in millibars at the opposite end. Such maps can be secured for school use from the Superintendent of Documents, Washington, D.C., by sending $3.00 for a yearly subscription. To avoid crowding, many of the code figures and signs around the stations have been omitted. An example of such station figures for Tampa is shown in the small square in the lower left-hand corner of the map.

The heavy black lines on the later weather maps represent the *fronts* of *air masses*. The pointed triangles scattered along the heavy lines represent *cold fronts*, at the ground if blackened, and above the ground if left clear. The tiny hemispheres along the heavy lines indicate *warm fronts*, at the ground if blackened, and above the ground if clear. The letters cPK in Maine represent a continental, polar air mass which is colder than the surface over which it is moving. The letters cPW in western Pennsylvania represent a continental polar air mass which is warmer than the surface over which it is moving.

**67. How are weather maps interpreted?** From long periods of observing weather conditions and weather maps, several facts concerning storms and their movements have been learned: (*a*) Cyclonic and anti-cyclonic storms generally travel in an easterly direction across the United States in fairly well-defined paths. From a study of air masses and wave fronts skilled observers can be remarkably accurate in their predictions. (*b*) The velocity of such storms usually varies from 400 to 700 miles daily, although storms are fickle; they may slow down, speed up suddenly, or remain stationary for several hours. (*c*) As storms pass successively over one place after another, they bring with them their own characteristic weather conditions. (*d*) As a rule, cyclonic and anti-cyclonic storms succeed one another at two- to three-day intervals. (*e*) High and low areas are generally from 500 miles to 1500 miles in diameter.

A skilled forecaster at some central station has before him the data from the 171 stations represented upon a United States weather map, and he has reports from some 500 other stations. From such data he can predict with remarkable accuracy. A good forecaster must be correct in his predictions at least 80% of the time, but he may fail if a storm suddenly changes its direction, slows down or accelerates, or if it loses or gains in intensity.

Usually weather predictions are made for 24 hours in advance, although predictions are sent out by daily papers or by radio at least twice daily. Large airports have their own forecasters and sometimes publish their own maps giving weather conditions for short periods in advance. Of especial importance are the reports of "height of ceiling," local thunder showers, and "range of visibility." During World War II in which airplanes played so prominent a part, the science of weather forecasting progressed by leaps and bounds. Had the invasion of Normandy on June 6, 1944, been attempted a week later, the weather conditions would have been so unfavorable that failure must have almost certainly been the result. No doubt many of the Allies' 13,000 planes would have been grounded and hundreds of their 4000 vessels would have been dashed



*Courtesy of Major H. Lee Wells, Jr., Omaha, Nebraska*

FIG. 76. The *Explorer II* almost ready for its flight into the stratosphere. This huge balloon was used to carry Captains Stevens and Anderson on their record-making flight into the stratosphere to a height of 72,395 ft. on Nov. 11, 1935. The gas bag, 192 ft. in diameter, and about 300 ft. in height, held 3,700,000 cu. ft. of helium. The gondola, 9 ft. in diameter, was equipped with a radio, a supply of liquid air for air-conditioning, and a movie camera for taking film from the air. Barometers were carried for measuring altitudes, thermometers for finding inside and outside temperatures, and other instruments. Spores were exposed outside, and then studied for germination. Samples of air were taken at different altitudes. At the highest altitudes the sun was blinding, but the sky appeared nearly black. Very fine shot and bags of lead dust were carried as ballast. (See *National Geographic Magazine*, Jan. 1936.)

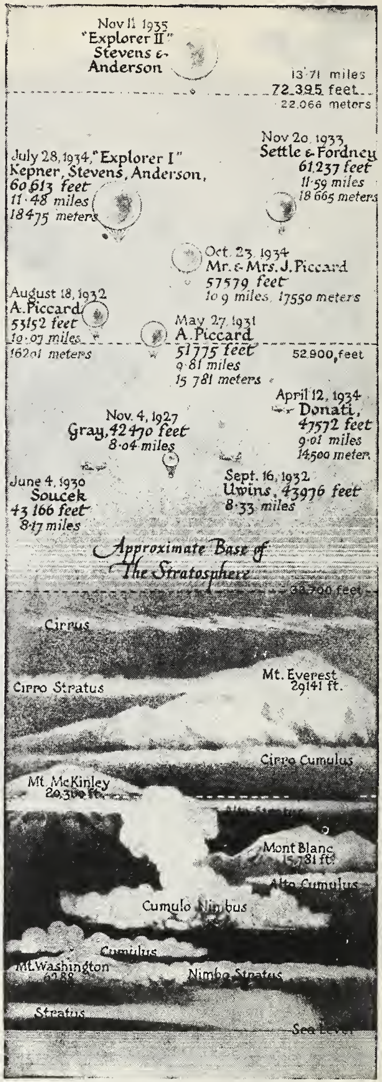
to pieces, in a disaster similar to that of the Spanish Armada.

Forecasts made 48 hours ahead are fairly reliable. For example, a storm whose center is in the Chicago area is likely to reach Cleveland or Buffalo about a day later, and to arrive in Albany or New York about two days later. Much progress has been made in long-range forecasting, for a week or more in advance, but the forecasts given in some almanacs for an entire year have no *scientific value*.

**68. How high does the atmosphere extend?** This question cannot be answered accurately. At an elevation of three miles, the pressure of the air is only about half as great as at sea level. Colonel Mario Pezzi reports that he ascended in a cabin airplane to a height of 56,016 ft., or more than 10.5 mi. At such altitudes the air is too rare to support respiration, and aviators must carry a supply of oxygen. Electrically heated fur suits are worn by aviators at high altitudes, since the temperature falls to more than sixty degrees below 0° C. Airplane engines are equipped with superchargers to supply the engine with more oxygen when flying in rarefied air. Without a supercharger, an airplane engine at a height of 20,000 ft. loses about 60% in efficiency.

On Nov. 11, 1935, Anderson and Stevens ascended in a gondola carried by a huge balloon up into the stratosphere to an altitude of 72,394.8 ft., or more than 13.7 mi. The *stratosphere* is that portion of the upper atmosphere in which temperature is almost uniform and in which clouds of water do not form. The portion of the atmosphere below the stratosphere is called the *troposphere*. (See Fig. 77.)

Self-registering instruments have been carried by small balloons to a


Nov 11 1935
"Explorer II"
Stevens & Anderson
13·71 miles
72,395 feet
22,066 meters
July 28, 1934, "Explorer I"
Kepner, Stevens, Anderson,
60,613 feet
11·48 miles
18475 meters
Nov 20, 1933
Settle & Fordney
61,237 feet
11·59 miles
18 665 meters
Oct. 23, 1934
Mr. & Mrs. J. Piccard
57579 feet
10·9 miles, 17550 meters
August 18, 1932
A. Piccard
53152 feet
10·07 miles
16201 meters
May 27, 1931
A. Piccard
51775 feet
9·81 miles
15 781 meters
52,900 feet
April 12, 1934
Donati,
47572 feet
9·01 miles
14500 meters
Nov. 4, 1927
Gray, 42470 feet
8·04 miles
June 4, 1930
Soucek
43 166 feet
8·17 miles
Sept. 16, 1932
Uwins, 43976 feet
8·33 miles
Approximate Base of The Stratosphere
Cirrus
Cirro Stratus
Mt. Everest 29141 ft.
Cirro Cumulus
Mt. McKinley 20,300 ft.
Alto Stratus
Mont Blanc 15,781 ft.
Alto Cumulus
Cumulo Nimbus
Cumulus
Mt. Washington 6288
Nimbo Stratus
Stratus
Sea Level

*Reproduced by special permission of National Geographic Magazine*

FIG. 77. Man is ambitious. He is constantly striving to reach higher altitudes by flights into the stratosphere. Nearly every year some aviator soars a little higher into the stratosphere and establishes a new altitude record. In military service, aviators are interested in the rate of climb, too.

height of nearly 22 miles. When the balloons expand in such rare atmosphere they burst and release the instruments, which are protected by parachutes against injury from rapid fall.

From the darkening of the moon by the earth's atmosphere at the beginning of an eclipse, from the height of the aurora borealis, and from observations of the height at which meteors entering our atmosphere begin to glow, it is estimated that rarefied portions of the atmosphere extend to a height of from 125 to 500 miles. Fig. 77 shows the results of man's explorations. He still has a long distance to go.

## QUESTIONS

1. How would you prove that air has weight?
2. How would you prove that air exerts pressure?
3. Why must a mercurial barometer be hung in a vertical position? What is the effect of inclining such a barometer?
4. Explain why hollow bodies are not crushed by the pressure of the atmosphere.
5. Suppose that a little moisture is introduced into the space above the mercury in a barometric tube. How will the reading be affected?
6. If a little air is introduced into the space above the mercury in a barometric tube, how is the reading affected?
7. What would happen if a small pinhole were made in the top of the tube of a barometer?
8. Does the diameter of a Torricellian tube have any effect upon the height of the mercury column?
9. How would the reading of a barometer be affected if it were carried down into a deep mine?
10. How does the air get into your lungs in ordinary breathing?
11. The piston in the cylinder of an automobile produces a partial vacuum in the cylinder. How does the mixture of gasoline and air get into the cylinder?
12. State two reasons why mercury is a suitable liquid to use in barometers.
13. Exhaust the air from a bottle fitted with a stopcock, as shown in Fig. 78. When the tube is held below the surface of water, a stream of water flows into the bottle when the stopcock is opened. Explain.
14. Fill a bottle with water, cover it with a glass plate, and invert it in a pan of water. (See Fig. 79.) Why does not the water flow out of the bottle when the glass plate is removed? Put one end of a glass tube under the mouth of the bottle and blow through the tube. Why does the air rise in the bottle? Why does the water flow out of the bottle as the air enters? Gases are often collected in this way in a chemical laboratory. This method is called "water displacement."
15. Liquids do not flow readily from a tap at the end of a barrel unless the bung at the top is removed. Explain.
16. A person wishing to pour condensed milk from a can usually punches two holes in the top, at opposite sides. Why is a second hole necessary?
17. Generally there is a tiny hole in the cap of a fountain pen. Explain its purpose.
18. Pipettes are used in measuring liquids. As the air is sucked out of the pipette when its tip is beneath the surface of the

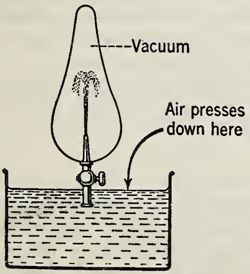


Fig. 78. Fountain in a vacuum.

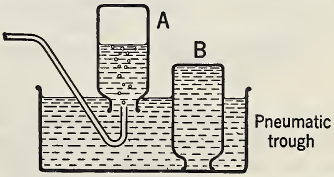


Fig. 79. In the laboratory gases may be collected by water displacement.

liquid, the liquid rises in the pipette. Explain. If a finger is held tightly over the top, the liquid does not flow out even when the tip is raised above the surface. Explain. (See Fig. 80.)

19. Compare the action of a pipette with that of a medicine dropper or fountain-pen filler.

20. The first barometer constructed was a water barometer. The bowl was in the cellar and the tube extended up through the house above the roof. A wooden figure floating on the water rose above the roof in fair weather and retreated into the attic in foul weather. The owner was quite successful in forecasting the weather and was compelled to destroy his barometer because his neighbors accused him of wizardry. State the advantages of a water barometer and also give its defects.

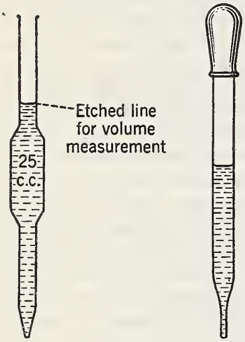


Fig. 80. Air pressure keeps the water from flowing out of the tips of the pipette and pen filler, or medicine dropper.

21. A few years ago some workmen used steam to clean the interior of a tank car. The opening in the top of the car was then tightly closed. A few minutes later the steel car collapsed. Explain.

22. What is the difference between "fair" and "clear" as used in weather forecasts?

23. The weather forecaster is correct in his predictions about 80% of the time. Explain why he errs in some cases.

24. Why would you expect "long range predictions" of three or four days in advance to be more accurate for the eastern part of the United States than for the western part?

25. Suppose that a low barometer area has been moving eastward across the United States for three days at a speed of 400 miles per day. If this storm suddenly increases in velocity to 700 miles per day, how would it be likely to affect the weather man's predictions for New York City?

26. Compare weather conditions, United States forecasts, and almanac predictions for a period of two weeks. Make a record of your findings.

27. The cap on the gasoline tank of an automobile has a small hole in it. What is its purpose?

28. Give as many equivalents as you can for the value of atmospheric pressure at sea level.

## PROBLEMS

### Group A

1. Suppose that your laboratory is 36 ft. long, 24 ft. wide, and 14 ft. high. What does the air in the room weigh?

2. A barometer at the base of a cliff reads 30.1 in. At the top of the cliff it reads 29.8 in. high. Calculate the height of the cliff.

3. If a barometer is sunk in water until the surface of the mercury in the bowl is 40.8 in. below the surface of the water, how will the barometer reading be affected?

4. What is really meant by the term "pressure of 10 atmospheres"?

5. How high a water column is needed to exert the same pressure as 76 cm. of mercury?

### Group B

6. The palm of your hand probably has an area of about 12 sq. in. How much force would be needed to hold your hand palm upward if the air beneath your hand were removed?

7. A pair of Magdeburg hemispheres has a diameter of 4.2 in. If a perfect vacuum could be obtained inside the hemispheres, what force would need to be used to pull the hemispheres apart? (Hint: Calculate

the air pressure on a circle 4.2 in. in diameter.)

8. The Magdeburg hemispheres used by Otto von Guericke were 22 in. in diameter. What force was needed to separate them? Why do we calculate the pressure upon the area of a circle?

9. If a tube 33 inches long is needed for a mercury barometer, how long a tube will be needed for an alcohol barometer, if the alcohol has a sp. wt. of 0.8?

10. Calculate the total pressure, air and water, upon a person who dives in sea water to a depth of 40 ft.

## 2. Compressibility and Expansibility of Gases

**69. Gases expand.** If we put a pint of milk in a quart bottle, the milk does not expand and fill the entire bottle. If we puncture an inflated tire, the air that was inside the tire expands as it escapes and occupies much more space than it did formerly. We can easily measure the volume of a liquid, such as milk or water, but the volume or space that a gas occupies depends upon the pressure to which it is subjected. Suppose we blow up a rubber balloon until it is about half inflated. Next let us put it under a bell jar and exhaust the air that surrounds the balloon. As we remove the air from the bell jar, we are reducing the pressure on the outside of the balloon. The gas inside expands and increases the volume of the balloon decidedly. If we let the air back into the bell jar, the balloon will shrink to its former size. This experiment shows that gases are perfectly elastic. (See Fig. 81.)

**70. What are standard temperature and pressure?** If a carpenter wishes to cut a board 12 ft. long, he does not bother to read the thermometer or the barometer. In selling gasoline, the attendant does not read the thermometer as he measures out each gallon. It is true that the dimensions of both solids and liquids do vary to some extent with the temperature and the pressure applied to them, but the variation is so small that it is usually neglected. For very great accuracy, both temperature and pressure corrections become necessary in the measurement of solids and liquids. For example, the *standard meter is exactly one meter long only when the temperature is 0° C.*

Because gas volumes vary so much, it is always necessary to consider both the temperature and the atmospheric pressure when we wish to measure them. To prevent confusion, physicists have agreed upon *0° C. as the standard temperature* to be used. They have also agreed upon the pressure of a column of mercury *760 mm. high, or 76 cm., as the standard pressure.* The abbreviation S.T.P. is used to indicate *standard temperature and pressure.* For example,

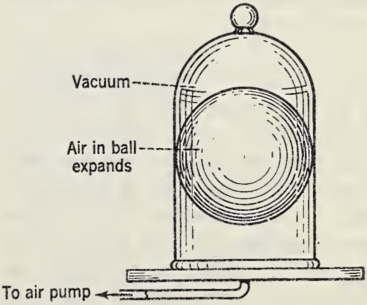


Fig. 81. Gases expand when the pressure upon them is decreased.

if we speak of a gas as having a volume of 1000 c.c., we mean that that is the volume which the gas occupies when its temperature is 0° C., and the pressure applied to it is equal to one atmosphere, or 76 cm. of mercury. At a different temperature and pressure, its volume will be decidedly different.

**71. Liquids are not easy to compress.** It is so hard to compress liquids that we consider them almost incompressible. Water, for example, is so nearly incompressible that it takes the stupendous pressure of 20 tons to reduce the volume of 1 cu. in. by only 0.1. This means that the water at the bottom of the ocean is only slightly more dense than it is near the surface.

We learned, however, that gases are easily compressed, and that the air at sea level is about twice as dense as it is at the top of Mt. Blanc. The air at sea level is compressed by the weight of the upper layers of air that it sustains.

**72. What is Boyle's law?** Robert Boyle was the first person to perform experiments upon what he called the "springiness of the air." No doubt others had known something of compressed air, but no one had taken the trouble to find out how the volume of a gas is really affected by the pressure which it sustains.

Boyle used a J-shaped tube for his study. He added enough mercury to fill the bent portion of the tube and adjusted the levels so that the mercury would stand ~~at~~ the same height in both arms of the tube. Then he had a volume, *V*, of air confined in the short arm of the tube. Next he measured the length of the tube so that he could determine the volume of gas confined. He knew that this gas must be under the same pressure as the air, because the mercury levels were equal. (See Fig. 82A.)

1. By reading the barometer, he could find the exact pressure to which the enclosed volume of air was subjected. Let us call that pressure *P*. Next he added more mercury to the long arm of the tube, as shown in Fig. 82B.

2. By measuring the length of the column of air enclosed, he could determine the new volume, *V′*. He could find the new pressure, *P′*, by measuring the length of the mercury column, *ab*, and adding that length to the barometer reading.

As a result of several trials with such an apparatus, Boyle found that increasing the pressure upon a volume of confined gas reduced its volume correspondingly. Doubling the pressure reduced the volume to one-half; trebling the pressure reduced the volume to one-third. BOYLE'S LAW may be stated as follows: *The volume of any dry gas, the temperature remaining constant, varies inversely with the pressure sustained by it.*

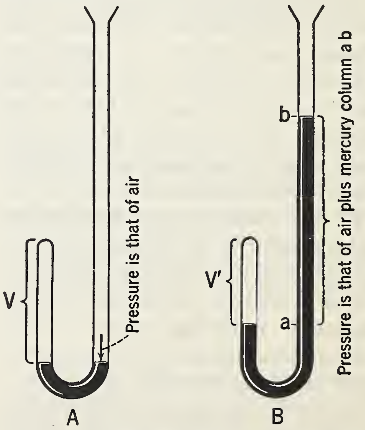


FIG. 82. Apparatus used to demonstrate Boyle's law.

**★73. Boyle's law can be shown graphically.** Suppose that we start with 2000 c.c. of gas measured at a pressure of 200 mm. of mercury. By experiment, it may be shown that if we subject this volume of gas to the successive pressures given along the margin of Fig. 83, its volume, $V$, will be reduced to the amount shown opposite the corresponding pressure, $P$. Using the volumes as ordinates and the pressures as abscissas, we obtain an *inverse* proportion graph. Since one factor increases as the other decreases, *the product of the volume and its corresponding pressure is always a constant quantity.* Stated algebraically,

$$VP = \text{a constant.}$$

In all cases, except under *very high* pressures,

$$VP = V'P'.$$

$V'$ represents the *new* volume, and $P'$ the *new* pressure.

**74. How does pressure affect gas densities?** Since there is no change in the weight of the gas during the changes in volume given in the preceding section, evidently *the density of a gas increases in direct proportion to the pressure it sustains.* A liter of air weighs 1.29 gm. at a pressure of one atmosphere, but a liter vessel can hold 5.16 gm. of air under a pressure of four atmospheres. In the latter case, the air is four times as dense.

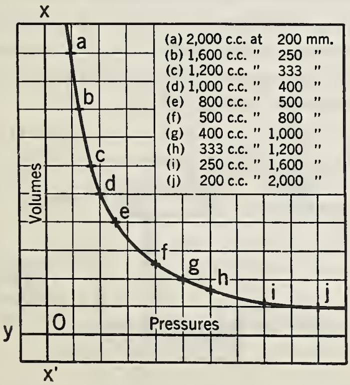


FIG. 83. Curve to show simple inverse proportion.

PROBLEM. Given 500 c.c. of gas under a pressure of 750 mm. of mercury. What volume will the gas occupy at a pressure of 800 mm.? If this gas has a density of 1.5 gm. per liter under the original pressure, what will be its density under the new pressure?

*Solution.* Since the pressure is increased, the volume will be reduced. The new volume will be $\frac{750}{800}$ of the original volume. $\frac{750}{800}$ of 500 c.c. = 468.8 c.c. Or, $VP = V'P'$. Then, $500 \times 750 = V' \times 800$. Whence, $V' = 468.8$ c.c.

Since the pressure is increased, the density will be increased. The new density will be $\frac{800}{750}$ of the original density. $\frac{800}{750} \times 1.5$ gm./liter = 1.6 gm./liter.

**75. How does the exhaust pump work?** A pump used to exhaust air from vessels and produce a vacuum was invented by Otto von Guericke in 1650. For such a pump, there must be a cylinder, a piston, and valves. The piston fits the cylinder so tightly that air cannot pass, and a rod is attached to it so that the piston can be moved up and down, or to and fro, from one end of the cylinder to the other. A valve acts like a policeman at the exit of a one-way street. He per-

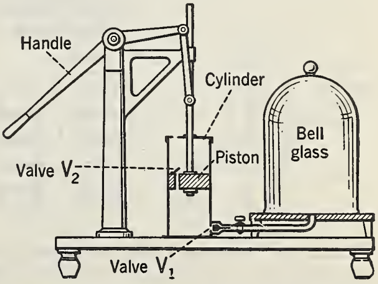
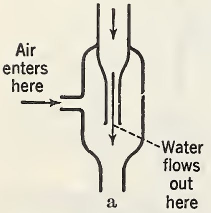


Fig. 84. Such a pump is used for pumping air or other gases. It is a vacuum pump.

mits traffic to move in one direction *only*. The valve opens to permit air to flow in one direction, but closes so that it cannot flow the other way.

While the piston represented in Fig. 84 is pulled up the cylinder, the valve $V_2$ remains closed. The air that was above the piston is pushed out through a small hole in the top of the cylinder. A *partial vacuum* is produced below the piston as it rises. The air in the bell jar expands, and part of it flows through the valve $V_1$ into the partial vacuum in the lower end of the cylinder. When the piston is lowered again, the valve $V_1$ closes so that the air cannot flow back into the bell jar. The air then forces its way up through the valve $V_2$ of the descending piston. On the next upstroke of the piston, the operation is repeated. The air above the piston is pushed out, and more air flows over into the lower end of the cylinder from the bell jar. Each upstroke of the piston removes part of the air from the vessel that is to be exhausted.

Supposing the cylinder and the bell jar to be both of the same size, one half the air will flow into the cylinder during the upward stroke of the piston, and one half of the air will be removed at the completion of one stroke of the pump. During the next complete stroke, one half of the remaining air or one fourth of the original amount is removed. The next stroke removes one half of what remains, or one eighth of the original amount. The action continues thus until the expansive force of the air finally becomes too weak to operate the valves of the pump.



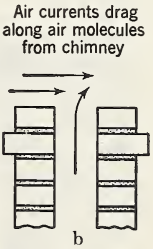


Fig. 85a. A vacuum can be produced by an aspirator. Water drags along with it the air molecules.

Fig. 85b. Wind blowing over top of chimney produces a partial vacuum.

**★76. What is the aspirator?** A suction pump, or aspirator, is often used in the laboratory to produce a partial vacuum. It is screwed to a water faucet, and the vessel to be evacuated is attached to the tube on the side of the pump. (See Fig. 85a.) As a current of water flows rapidly through the inner tube, it drags along with it air molecules from the vessel to be exhausted. The air in the vessel expands and more molecules are carried away by the running water. In this manner, quite a good vacuum can be produced in a short time.

**★77. What are ejectors?** When the wind blows across the top of a chimney, the rapidly moving current of air carries along with it some of the gas molecules within the chimney. (See Fig. 85b.) The gases within the chimney expand, and their density is decreased. For this reason a chimney draws much better on a windy day.

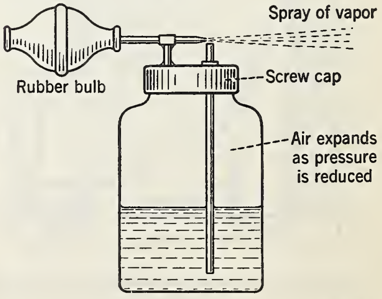
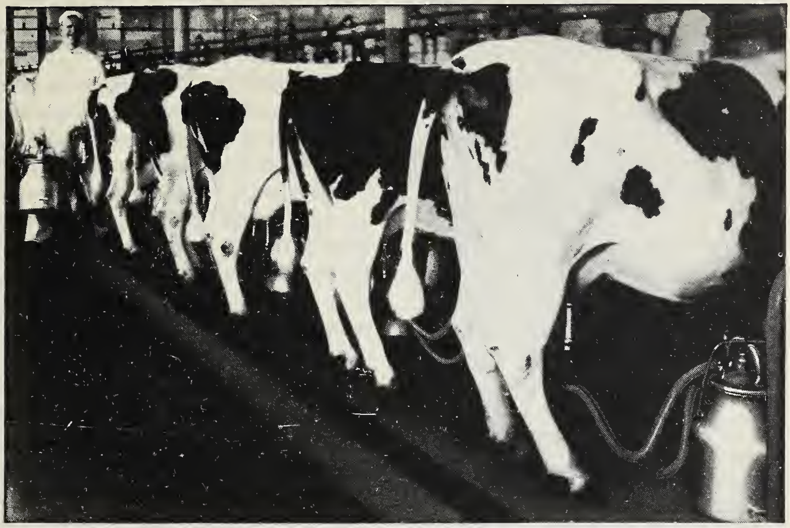


Fig. 86. The atomizer as used to form a spray.



*Courtesy of the de Laval Separator Company*

FIG. 87. Tubes lead from the cow's udder to a can, inside which a vacuum is produced by means of a pump.

The *atomizer* is another application of the *ejector* principle. A small tube extends down through the stopper into the liquid in the bottle, as in Fig. 86. Fastened to the stopper is a tube set at right angles to and just on a level with the end of the vertical tube. When the bulb, which is attached to the horizontal tube, is squeezed, a stream of air is forced across the top of the tube, thus reducing the air pressure inside, just as the wind blowing across the top of a chimney reduces the air pressure inside. The air inside the bottle then expands and pushes the liquid out through the tube, where it is broken up into spray by the blast of air from the bulb.

**78. What are some uses of the exhaust pump?** Some type of exhaust pump is used whenever it is necessary to remove a part or all of the air from a container. Unless the air is removed from an electric light bulb, the filament will burn. In some types, the bulb is then refilled with a gas which has no effect upon the filament. In making X-ray bulbs, radio tubes, and thermos bottles, an exhaust pump is used. The milking machine of Fig. 87 is a common application of the vacuum pump.

Liquids boil at a lower temperature in a vacuum than under air pressure, and they evaporate much more rapidly in a vacuum. The principle of vacuum drying is used when dyestuffs, chemical crystals, etc. are dried in *vacuum pans*. Some of our *dried* or *dehydrated* foods have had much of the water they contained removed by drying them in a vacuum pan.

In sugar refineries, vacuum pans are used during the evaporation of the sugar solution, since evaporation occurs more rapidly and a lower tempera-

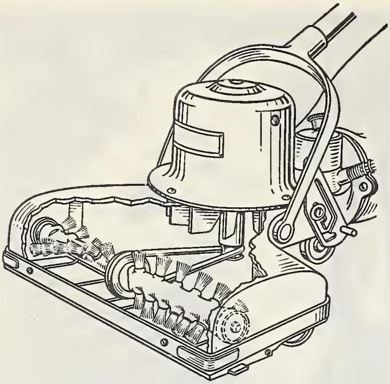


Fig. 88. The revolving brush beats the rug gently, and the dirt is pushed into the partial vacuum produced by an electric motor.

ture may be used to avoid danger of scorching the crystals.

The *vacuum cleaner* also furnishes a practical application of the exhaust pump or exhaust fan. In the latter case, a fan is driven by an electric motor. The fan pushes the air away in front of the blades, and leaves a partial vacuum on the other side of the fan. As the air rushes in through the mouthpiece of the tube leading to the fan chamber, it carries with it the dust particles from the article that is being cleaned. A rotary brush is sometimes used to sweep and beat the rug or carpet at the same time in order to loosen the dirt. (See Fig. 88.)

**79. How does the compression pump work?** The bicycle pump, or automobile tire pump, furnishes a common example of compression pump. Such pumps are used to push or crowd more air into a container. In one of the simple types, shown in Fig. 89, a leather disc attached to the piston permits the air to flow past it in one direction, but not in the other. Hence it takes the place of a valve in the piston. The other valve may be placed in the outlet tube; with pneumatic tires a valve is placed in the valve stem of the tire itself.

Fig. 90 shows the construction of one type of compression pump. The piston has no valves, and fits the cylinder so tightly that air cannot pass. The valves are so arranged that air enters through one as it leaves through the other. On the upstroke of the piston the air above it is pushed out of the cylinder. Valve $V_1$ opens to permit air to enter through $A$. On the downstroke this valve closes and valve $V_2$ opens as the piston pushes the air out of the lower part of the cylinder.

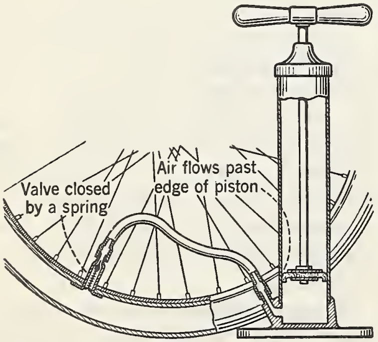


Fig. 89. A simple compression pump used to inflate a pneumatic tire.

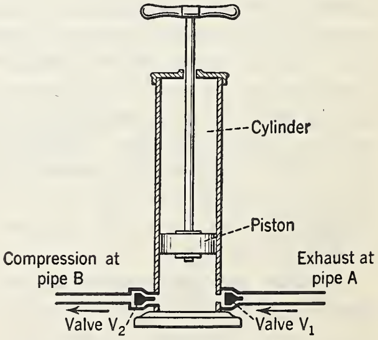


Fig. 90. This compression pump may also be used as an exhaust pump.

Such a pump may be used as either an exhaust or a compression pump. If a vessel is attached at $A$, it will be exhausted as the pump operates, while air is being compressed in a vessel attached at $B$. Thus, a reversal of the direction in which the valves open may convert a compression pump into an exhaust pump, or vice versa.

**80. What uses are there for compressed air?** For two reasons there are many uses for compressed air: (*a*) When air is put under a pressure of several atmospheres, it is capable of exerting great expansive force. (*b*) It is particularly satisfactory, since strong-walled tubes can be used to transmit this force to considerable distances. We use compressed air to drive our machines, to stop our railroad trains, and to carry mail and small parcels. For greater comfort, we ride upon it.

1. *Pneumatic tires.* The compressed air in our automobile tires forms an elastic cushion to absorb the shocks which we encounter on rough roads. As we pump up a pneumatic tire, we are applying Pascal's law to gases. The pressure applied to the valve stem is transmitted undiminished to every unit area of the inside of the tire.

2. *The Westinghouse air brake.* The flanged wheel, invented by Stevens, and the air brake, invented by Westinghouse, have made it possible to run trains at high speeds. After Westinghouse conceived the idea of a set of brakes which could be applied by the engineer to every car in the train at the same time, he was at a loss to find a satisfactory fluid to operate the brakes. The story is told that a young lady called at his office to sell him a magazine. At first he refused to buy, but reconsidered when he took a moment to look at the young lady. In that magazine he found an article describing the use of compressed air for operating some of the tools used for tunnel construction work in Europe. He decided then to try compressed air for operating his newly invented brakes. (See Fig. 91.)

*Courtesy of Westinghouse*

FIG. 91. George Westinghouse (1846-1914) was an American inventor. He not only invented the air brake, but he was an organizer of great ability.

★The air brake may be operated directly from the engine or it may operate automatically from an auxiliary reservoir of compressed air stored under the car itself. In Fig. 92, $P$ is a pipe connected with the main reservoir on the engine, in which a compressor maintains a pressure of about five atmospheres. The reservoir communicates with $P$ through a triple valve. This valve maintains communication between $P$ and the reservoir and shuts out the air from $C$, as long as the pressure from the engine is supplied to $P$. When this pressure is diminished, either intentionally by the engineer or accidentally by the breaking of the coupling, the valve opens in such a way that air from the reservoir flows into $C$ and forces the brake piston to the left, thus setting the brakeshoes against the wheels. Readmission of air through $P$ lets the air in $C$ escape and the spring releases the brakes.

3. *Diving bells and diving suits.* If we force a tumbler under water, mouth downward, the pressure of the water compresses the air in the tumbler to some extent, the amount of compression depending upon the depth. The air in a *diving bell* is compressed in a similar manner as it is lowered in the water. (See Fig. 93.) In the modern diving bell the workmen are supplied with air forced down through a tube connected with a compressor at the surface. The air is supplied fast enough to force all the water out of the bell and keep a stream of bubbles flowing out from its lower edges. (See Fig. 94.)

The *diving suit* is sometimes supplied with compressed air in the same manner as the diving bell. In other cases the diver has a self-contained apparatus and is independent of a compressed air supply line. He carries a tank of compressed air. By opening a valve he permits air to escape just fast enough to keep his suit filled with air. A constant stream of bubbles passes out through a valve in his suit. (See Fig. 95.)

4. The *pneumatic caisson* is used for constructing bridge piers or foundations under water. The caisson is open at the lower end and it is weighted so that it will sink, not only in water, but also into the mud at the bottom. (See Fig. 96.) Compressed air is used to keep the water out of the caisson. The workmen enter the caisson through air locks, or airtight doors, and material is passed down to them in the same manner. Thus the foundation may be built inside the caisson. For tunnel construction jacks are used to push forward a cylindrical shield as the material is removed by workmen. The tunnel lining is constructed inside the shield.

★5. *Pneumatic despatch.* In some large buildings compressed air is used for transmitting cash boxes and small packages. It has also been used for transmitting mail between the post office and the railroad stations, al-

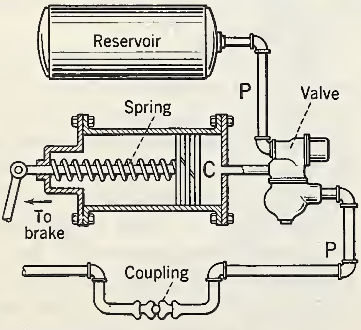


FIG. 92. The Westinghouse air brake.

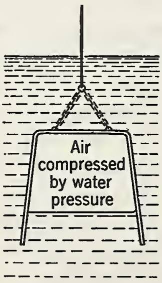


FIG. 93. Diving bell being lowered into the water.

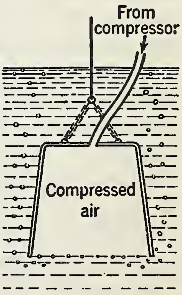
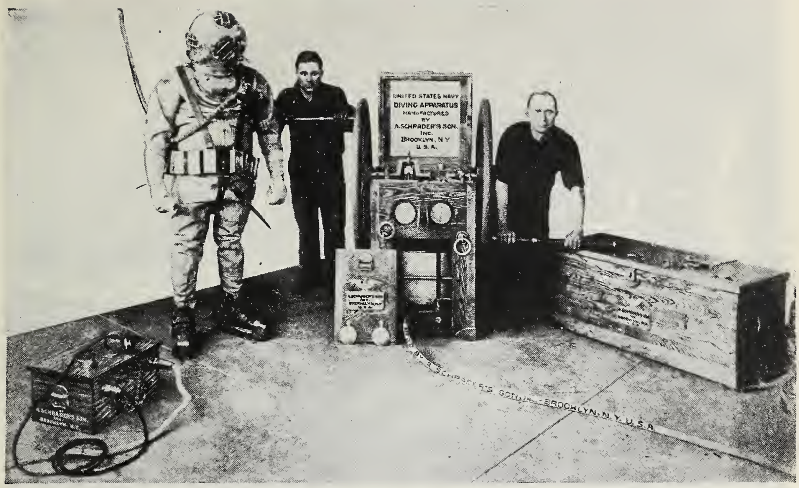


FIG. 94. Diving bell being supplied with compressed air.


UNITED STATES NAVY
DIVING APPARATUS
MANUFACTURED
BY
A.SCHRADER'S SON.
INC.
BROOKLYN, N.Y.
U.S.A.
A. SCHRADER'S SON INC. BROOKLYN, N.Y. U.S.A.

*Courtesy of A. Schrader's Sons*

FIG. 95. The diver is equipped with helmet, suit, and weighted shoes. The compressor is used to supply him with air.

though the system has in most cases been superseded by the motor truck. The cylindrical carrier, which is slightly smaller than the tube, has packing rings near the ends to make it fit the tube fairly tightly without much friction. An exhaust pump at the receiving end and a compression pump at the transmitting end of the tube produce a difference of pressure that is sufficient to drive the carrier through the tube with considerable speed.

6. *Other uses for compressed air.* Many tools are operated by compressed air. The list includes *riveting hammers, rock-drills, the sand blast for cutting and polishing,* and *some rotary tools.* The *bellows* are used to produce a forced draft for making a blacksmith's forge hotter, or to supply compressed air for organ pipes, or for starting fires. They are indirectly used to produce the partial vacuum needed for the operation of player pianos.

Mines and large buildings are often ventilated by compressed air. It is used to operate car doors and for various regulating devices. In submarines it is used to force the water from the various chambers, and it operates the propellers which drive torpedoes.

**81. Compressed air ventilates the tunnels beneath the Hudson River.** Several years ago the Holland Tunnel

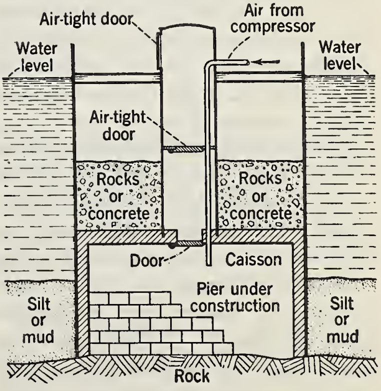
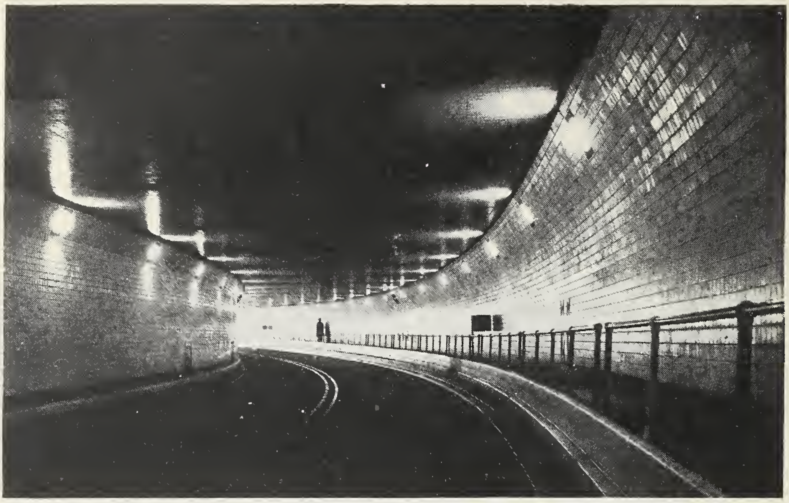

Air-tight door
Air from compressor
Water level
Water level
Air-tight door
Rocks or concrete
Rocks or concrete
Door
Caisson
Pier under construction
Silt or mud
Silt or mud
Rock

FIG. 96. Sectional view of a pneumatic caisson.



*Courtesy of the Port of New York Authority*

Fig. 97. Inside view of the Lincoln Tunnel which was built to carry vehicular traffic under the Hudson River.

was built for vehicular traffic under the Hudson River from New Jersey to New York City. Recently the Lincoln Tunnel was opened. The so-called Holland Tunnel consists of two tunnels, each 29 ft. 6 in. in diameter, laid side by side beneath the Hudson River. More than a mile, 5,480 ft., of the length of these tunnels is beneath the river. (See Fig. 97.) This tunnel is designed to have a capacity of 2000 automobiles per hour. Several million cars have passed through the tunnels since they were opened.

The problem of ventilating these tunnels was quite as difficult as that of constructing them. Two ventilating buildings at either end were constructed to supply compressed air to remove the dangerous carbon monoxide which comes from the exhaust of all automobiles. In each one there are 21 large electric fans, part of them used to compress air, which then enters the tunnel near the bottom; and part of them for exhausting the air from the ducts at the top. Although these compressors can force 1,900,000 cu. ft. of air into the tunnels per minute, there is no longitudinal draft in the tunnel. The air rises to the exhaust ducts directly. (See Fig. 98.) Traffic moves rapidly through tunnels, and the ventilation seems to be adequate.

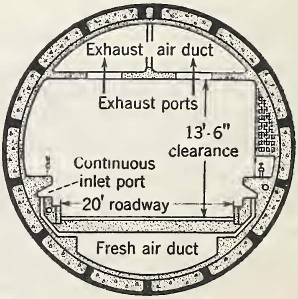


Fig. 98. Cross-sectional view of one of the tunnels under the Hudson River. The diagram shows how tunnel is constructed.

## QUESTIONS

1. Explain why air is not suitable for use in a hydraulic press.

2. Theoretically, can one produce a perfect vacuum with the type of air pump described in Section 75?

3. For trains what two advantages have air brakes over the old hand brakes?

4. What is meant by the expression "pressure of one atmosphere"? What is a pressure of "10 atmospheres"?

5. Do you think that the *Titanic,* which sank after hitting an iceberg, went all the way to the bottom or stopped part way down? Give a reason for your answer.

6. What are the advantages in the use of compressed air in transmitting pressure?

7. Blow through the jet tube of Fig. 99 as hard as you can. Explain the results.

8. Distinguish between the terms "direct proportion" and "inverse proportion."

9. Try to find out what happens when part of a freight train equipped with air brakes suddenly breaks loose from the forward part of the train. Explain.

10. Do you think the fuel gas supplied to your kitchen range is under a pressure of more or less than one atmosphere? Why?

11. Does it indicate high or low atmospheric pressure when the smoke from a chimney rises vertically? Is there any truth in the old saying, "It is a sign of rain when the smoke falls to the ground"?

12. Why does a chimney "draw" better on a windy day? Why should the top of a chimney be higher than any part of the roof of a building?

13. A man needs a certain number of grams of oxygen daily. Why must he breathe more deeply or more frequently at the top of a mountain than at the base?

14. Two small bottles are placed under a bell jar. (See Fig. 100.) The bottle *A* is partly full of a colored liquid and tightly stoppered. As the air is pumped out of the bell jar, the liquid flows through the bent tube into the bottle *B*. Explain. As we let air into the bell jar again, the liquid flows back into *A*. Explain.

15. How are gases that are to be sold commercially prepared for transportation? Why?

16. A tire is inflated at sea level to the proper pressure. Will the tire be "too hard" or "too soft" at the top of Pike's Peak? Explain.

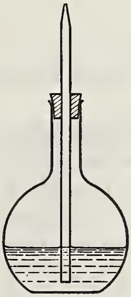


FIG. 99. Blowing into the flask compresses the air.

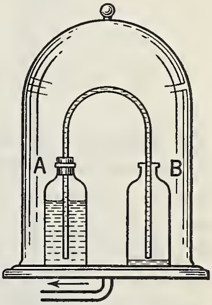


FIG. 100. The Bacchus' experiment with air pressure.

## PROBLEMS

### GROUP A

1. What will be the weight of 1 liter of air in a tire that is inflated to a pressure of five atmospheres?

2. A football has a volume of 250 cu. in. If it is inflated to a pressure of six atmospheres, what volume will the air inside occupy when released at a pressure of one atmosphere?

3. The volume of a given mass of gas is 1200 c.c. when the barometer reads 840 mm. What volume will the gas occupy when the pressure is reduced to 750 mm.?

4. Remembering that $VP$ = a constant, what successive pressures will be needed to change 800 c.c. of gas at 400 mm. to the following volumes? 1200 c.c.? 200 c.c.? 1600 c.c.? 100 c.c.? 2400 c.c.?

5. Suppose that you have 200 cu. ft. of oxygen gas under a pressure of 1 atmosphere. What pressure will be needed to crowd the gas into a container whose volume is 10 cu. ft.?

6. At a pressure of 1 atmosphere, 1 liter of oxygen weighs 1.43 gm. What will be the weight of 1 liter of oxygen under a pressure of 10 atmospheres?

### Group B

7. Suppose that the piston of an air brake has a diameter of 5 in. What force acts to set the brakes if the air in the reservoir is under a pressure of 6 atmospheres? (Consider the effective pressure as 5 atmospheres. Why?)

8. A diver is submerged to a depth of 210 ft. in sea water. To what total pressure, both atmospheric and liquid, is he subjected?

9. What change will there be in the volume of a bubble of gas released from the suit of the diver of Problem 8 as the bubble rises to the surface of the water?

10. A gas has a volume of 400 c.c. when the pressure sustained by it is 700 mm. What pressure will be needed to decrease the gas volume to 250 c.c.?

11. If air were subjected to a pressure of 1000 atmospheres, how would its density compare with that of water? Do you think that a block of wood would float in such air?

12. A tire has a volume of 900 cu. in. When it is inflated, a tire gauge shows a reading of 29.4 lb. per sq. in. What space will the volume of air in the tire occupy after a blowout when the pressure of the barometer is equivalent to 14.7 lb. per sq. in.? (Remember that a tire gauge reads zero when the pressure is one atmosphere.)

13. An automobile tire contains 100 cu. in. of air under an absolute pressure of 44.1 lb. per sq. in. What volume will the air occupy at normal atmospheric pressure?

14. Given 2500 cu. ft. of air under a pressure of 80 cm. of mercury. Find its volume under a pressure of 2 meters of mercury.

## 3. Other Pneumatic Appliances

**82. What is a lift or suction pump?** For cisterns or shallow wells, the *lift pump* is in common use. This pump, which is the type the Duke of Tuscany used, differs little in construction from the air pump. It consists of a cylinder, a piston, and two valves. The cylinder usually rests on a platform at the surface of the ground. From the lower end of the cylinder a pipe extends down into the well and dips beneath the surface of the water.

When one pushes down on the end of the pump handle, the piston, Fig. 101, is lifted. The valve $V_2$ in the piston is closed and the air above the piston is pushed out of the top of the cylinder, leaving a partial vacuum beneath the upward moving piston. The downward pressure of the air upon the surface of the water in the well pushes some water up through the pipe into the cylinder. The valve $V_1$ opens to permit the water to pass through. On the next downstroke of the piston, this valve closes so that the water cannot flow back into the well. The only place it can go is up through valve $V_2$ to occupy part of the space above the piston. The next upstroke of the piston *lifts* this water up so that it flows out through the spout. In the meantime, more water is being pushed up into the lower end of the cylinder by the air pressure on the water surface.

Because air pressure cannot lift water more than 34 ft., the lift pump cannot be used if the cylinder of the pump is more than 34 ft. above the level of the water in the well. You will recall that the pump used by the Duke of Tuscany failed when the well was more than 32 ft. deep. In actual practice, the lift pump is not used if the height to which the water is to be raised is more than about 28 ft. The leakage around the piston and through the valves makes it impossible to secure a perfect vacuum.

**83. What is a force pump?** In its construction, the *force* pump differs from the lift pump in only two essentials: 1. The piston is solid and has no valve in it. 2. The valve $V_2$ is located at the entrance to a pipe opening near the bottom of the cylinder, and from one side of it. (See Fig. 102.) In such a pump, the cylinder is placed down in a deep well at a distance of 15 or 20 ft. from the surface of the water. A long piston rod, attached to the pump handle above ground, extends down into the well where it is attached to the piston. The outlet pipe delivers the water from an opening in the side of the cylinder to the spout above the ground.

On the first upstroke of the piston, the air is pushed out of the upper part of the cylinder and a partial vacuum is formed beneath the piston and in the pipe leading down into the water. The air pressure on the surface of the water in the well pushes some water up into the pipe and the cylinder, just as in the case of the lift pump. On the downstroke of the piston, valve $V_1$ closes and the water from the cylinder is forced into the pipe. At each succeeding stroke of the pump it is forced higher in this pipe until it reaches the

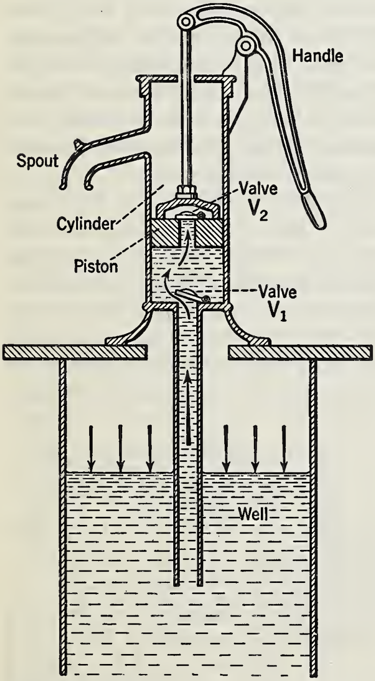


Fig. 101. Sectional view of the common lift pump. It is sometimes called a suction pump.

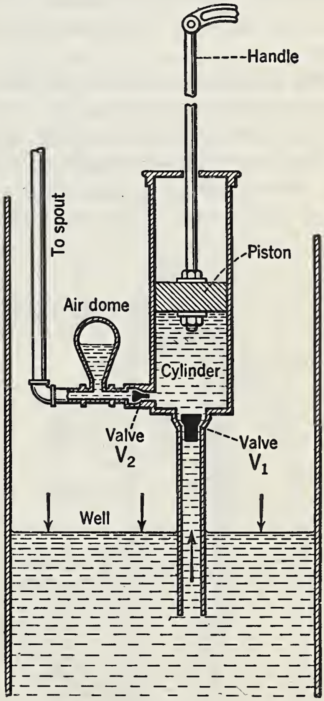


Fig. 102. The force pump is generally used for deep wells. The cylinder is down in the well, near the water surface.

spout and flows out there. The valve $V_2$ keeps it from flowing back into the cylinder during the upstroke of the piston. The student will find it easy to remember the valve arrangement if he keeps in mind the fact that the valves open in the direction *only* that one wishes the water to flow and that they open alternately.

Unless an air dome is used, the water from a force pump will come in spurts during the downstroke *only*. When the air dome is used, some water is forced into the dome during each downstroke, thus compressing the air in the dome. But this compressed air expands again during the next upstroke and pushes some of the water up the spout. Thus the dome causes a continuous flow of water.

**★84. How does a chain pump work?** We have represented in Fig. 103 an inexpensive, efficient pump widely used in country sections for shallow wells and cisterns. *AC* is a tube about $1\frac{1}{2}$ inches in diameter. When the ratchet wheel is turned by a crank, a continuous chain is pulled up through the tube and lowered into the well on the other side of the wheel. Rubber buckets which fit the pump tube airtight are inserted in the chain at intervals of 6 or 8 ft. As a rubber bucket is pulled up through the pump stock, *AC*, it removes the air, and the water follows, being lifted to the spout partially by atmospheric pressure and partially by the bucket that follows.

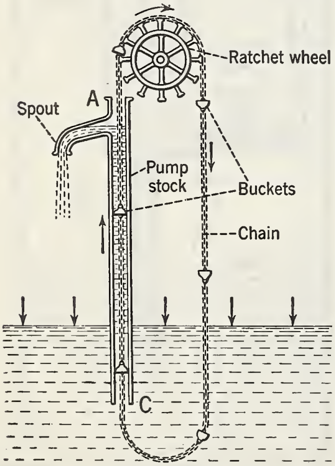


FIG. 103. The chain pump is extensively used for shallow wells or cisterns.

**85. How does a siphon work?** Quite often it is desirable to transfer liquids from barrels or heavy containers to other vessels without lifting the heavy containers, or incurring the risk of spilling the liquid in trying to pour it from a large container. A bent tube, having arms of unequal length, may be used to transfer liquids over an elevation from one container to another of lower level. A tube, generally made of rubber or glass, used for such purpose is called a *siphon*.

Suppose we fill the siphon tube *ABCD* with water and close the ends with our fingers while we invert the siphon in vessels of water, as shown in Fig. 104. From our study of air pressure and liquid pressure, we can understand why the water will flow through the siphon from the vessel *A* into the ves-

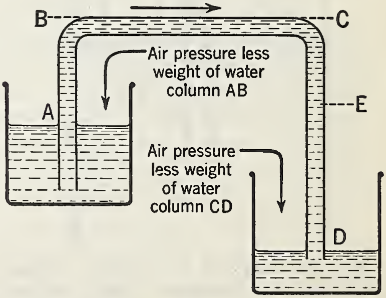

B
C
Air pressure less weight of water column AB
A
E
Air pressure less weight of water column CD
D

FIG. 104. The siphon is a convenient appliance.

sel *D*. The air pressure upon each liquid surface is equal to approximately 14.7 lb. per sq. in. Let us suppose that the short arm of the siphon, *AB*, is just one foot long. Then the water pressure from such a column of water is 0.43 lb. The *effective air pressure* at *A* then becomes only 14.27 lb. per sq. in. (14.7 − 0.43). Suppose that the long arm of the siphon, *CD*, is 3 ft. long. Then the air pressure at *D* is supporting a column of water 3 ft. high, and its effective pressure becomes only 13.41 lb. per sq. in. (14.7 − 1.29). Because there is less pressure at *D* than at *A*, the water will flow from vessel *A* into vessel *D*.

Since it is really the difference between the water pressures in the two arms of the siphon that makes the air pressures unequal, the rate of flow of the siphon must increase as we increase the difference in the lengths of the two arms. For every foot we increase the length *DE*, the pressure causing the siphon to flow increases 0.43 lb./sq. in. If we reduce the length *DE* to zero, then the siphon will stop flowing.

**86. What is the Cartesian diver?** The bottle imp, or Cartesian diver, illustrates several laws and principles of physics. By careful adjustment, it is possible to put into a small vial just enough water so that the specific weight of the combination, vial and water, will be the merest trifle less than that of water. Any pressure applied to the vial as it floats mouth downward, or any increase in its specific weight, will cause it to sink. (See Fig. 105.) Let us stretch a rubber membrane over the top of the cylinder and apply pressure to the membrane gradually. The vial descends slowly, rising again as we remove the pressure. Why?

1. The air beneath the membrane is compressed (easy compressibility of gases).
2. The increased air pressure is applied to the surface of the water, whence it is transmitted equally and undiminished in all directions (Pascal's law).
3. The gas in the upper part of the vial is compressed and the specific weight of the vial and contents is increased (specific weight and density).
4. The weight of the water displaced by the vial is now less than its weight, and it sinks (Archimedes' principle and laws of flotation).
5. As we remove the pressure, the air in the vial expands (expansibility of gases and Boyle's law) and pushes some water out of the vial. Its specific weight again becomes slightly less than that of water, and it rises to the surface (law of flotation). It is possible to use just enough pressure to keep the vial stationary beneath the surface of the water at any position.

The usual type of bottle imp is a toy devised by the philosopher Descartes. It consists of a small, hollow, imp-shaped figure with a hollow tail curled half way around the middle of the

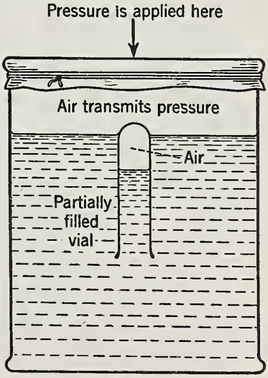


Fig. 105. The Cartesian diver, or bottle imp, demonstrates many laws and principles.

figure. There is a small opening in the tail for the entrance and exit of the water needed to change its relative densities.

**87. Fire extinguishers use pressure.** Fig. 106 represents a common type of soda-acid fire extinguisher. The extinguisher is charged with about $1\frac{1}{2}$ lb. of baking soda dissolved in water. The small bottle contains sulfuric acid. When the extinguisher is turned upside down, the acid spills out of the loosely stoppered bottle and unites chemically with the soda. Large quantities of carbon dioxide gas are set free. The high pressure produced by the rapidly escaping gas forces a stream of water and carbon dioxide gas into the fire with high effectiveness. The walls of the extinguisher are usually tested to withstand a pressure of 350 lb. per square inch.

**★88. The submarine is an old idea.** As long ago as the time of Alexander the Great, men conceived the idea of using submarine vessels in warfare. David Bushnell made a submarine during our Revolutionary War and tried to destroy some British ships in New York harbor by its use. He was unsuccessful, but the efficiency of submarines patterned after models made from the inventions of the Americans Lake and Holland was clearly demonstrated during the World War. (See Fig. 107.)

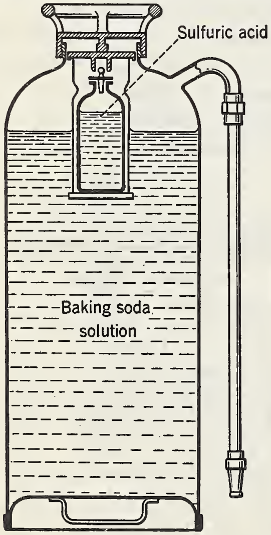
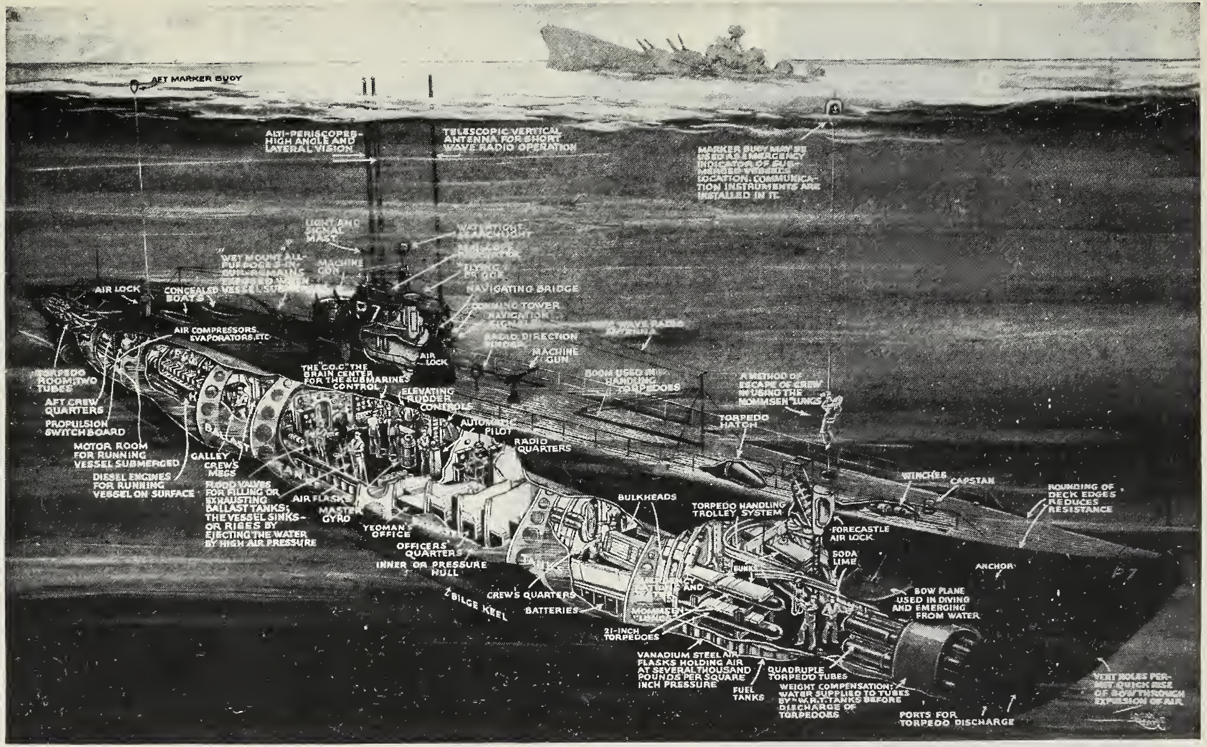


FIG. 106. Sectional view of a soda-acid fire extinguisher.

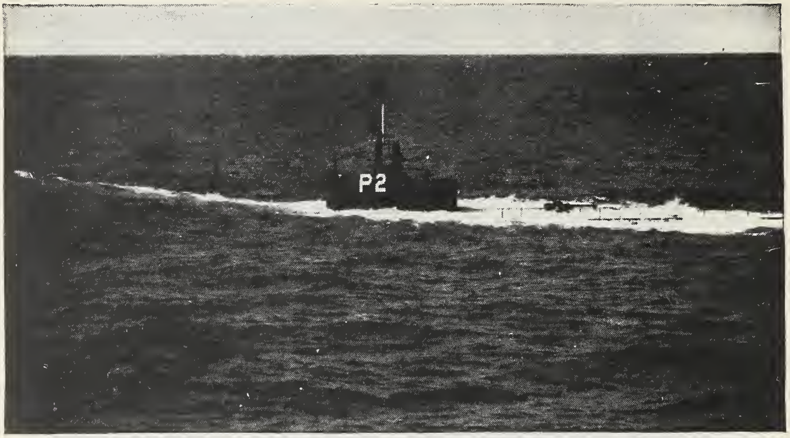
The principles used in the submarine are not unlike those used in the Cartesian diver. When a submarine is traveling on the surface, it floats just as any other ship does. Before the boat is submerged, certain compartments are opened to fill them with water. Thus the boat sinks deeper in the water, until only the deck and conning tower are awash. In the act of submerging, the propellers drive the boat forward, and the diving rudders are set at such an angle that the boat is pushed under water. To bring the submarine to the surface again, the diving rudders are set at such an angle that the bow of the boat is pushed upward. Compressed air is used to force the water out of the flooded compartments. (See Fig. 108.)

**89. Gases have buoyancy.** Clouds float in the air, and smoke is buoyed up by the weight of the air it displaces. Archimedes' principle applies to all fluids, gases as well as liquids. Just as objects that do not float in water lose part of their weight when submerged, so objects that are heavier than air lose part of their weight when submerged in air. An object that displaces exactly one liter of air will weigh 1.293 gm. more in a vacuum than it does in air at S.T.P. In other words, the buoyancy of air is 1.293 gm. per liter. The laws of flotation apply to all gases, and


AFT MARKER BUOY
ALTI-PERISCOPE-HIGH ANGLE AND LATERAL VISION
TELESCOPIC VERTICAL ANTENNA FOR SHORT WAVE RADIO OPERATION
MARKER BUOY MAY BE USED AS EMERGENCY INDICATOR OF SUBMERGED VESSEL'S LOCATION. COMMUNICATION INSTRUMENTS ARE INSTALLED IN IT.
LIGHT AND SIGNAL MAST
WATERTIGHT SEARCHLIGHT
MACHINE GUN
NAVIGATING BRIDGE
CONNING TOWER NAVIGATION
RADIO DIRECTION FINDER
MACHINE GUN
AIR LOCK
CONCEALED BOATS
AIR COMPRESSORS, EVAPORATORS, ETC
THE "C.O.C." THE BRAIN CENTER FOR THE SUBMARINES CONTROL
ELEVATING RUDDER CONTROLS
AUTOMATIC PILOT
RADIO QUARTERS
BOOM USED IN HANDLING TORPEDOES
A METHOD OF ESCAPE OF CREW IN USING THE MOMMSEN "LUNGS"
TORPEDO HATCH
TORPEDO ROOM: TWO TUBES
AFT CREW QUARTERS
PROPULSION SWITCHBOARD
MOTOR ROOM FOR RUNNING VESSEL SUBMERGED
DIESEL ENGINES FOR RUNNING VESSEL ON SURFACE
GALLEY
CREW'S MESS
FLOOD VALVES FOR FILLING OR EXHAUSTING BALLAST TANKS; THE VESSEL SINKS—OR RISES BY EJECTING THE WATER BY HIGH AIR PRESSURE
AIR FLASKS
MASTER GYRO
YEOMAN'S OFFICE
OFFICERS QUARTERS
INNER OR PRESSURE HULL
BILGE KEEL
CREW'S QUARTERS
BATTERIES
BULKHEADS
TORPEDO HANDLING TROLLEY SYSTEM
WINCHES
CAPSTAN
ROUNDING OF DECK EDGES REDUCES RESISTANCE
FORECASTLE AIR LOCK
SODA LIME
BUNK
AND
MOMMSEN "LUNGS"
21-INCH TORPEDOES
ANCHOR
BOW PLANE USED IN DIVING AND EMERGING FROM WATER
VANADIUM STEEL AIR FLASKS HOLDING AIR AT SEVERAL THOUSAND POUNDS PER SQUARE INCH PRESSURE
FUEL TANKS
QUADRUPLE TORPEDO TUBES
WEIGHT COMPENSATION: WATER SUPPLIED TO TUBES BY "W.R.T." TANKS BEFORE DISCHARGE OF TORPEDOES
PORTS FOR TORPEDO DISCHARGE
VENT HOLES PERMIT QUICK RISE OF BOW THROUGH EXPULSION OF AIR
P7

*Courtesy of Look, Inc.*

FIG. 107. Sectional view of a submarine.



*Courtesy of the U. S. Navy Recruiting Bureau*

FIG. 108. The submarine chambers are filled to lower the vessel to the awash position before the vessel dives beneath the surface.

an object will rise in air if the weight of the air it displaces is greater than its own weight.

**90. Balloons and airships make use of the buoyancy of air.** A balloon consists essentially of a strong, airtight bag filled with some gas lighter than air. It will rise if its weight plus the weight of the gas it contains is less than the weight of the air it displaces. If the balloon is filled with hydrogen, a gas which weighs only 0.09 gm. per liter, then every liter of air the balloon displaces exerts a lifting force equal to the difference between the weight of one liter of air and one liter of hydrogen. 1.29 gm. − 0.09 gm. = 1.2 gm. While it is the buoyant force of the air displaced that causes a balloon to rise, it is commonly spoken of as the *lifting force* of hydrogen. For example, the *so-called lifting force of hydrogen is 1.2 gm. per liter*. Since there are 1000 liters in a cubic meter, the lifting force of hydrogen is equal to 1200 gm. per cu. m. or approximately 1.2 oz. per cu. ft. (See Fig. 109.)

Hydrogen is the lightest gas known, but it is flammable. After the *Hindenburg* had made several trips across the Atlantic Ocean, the hydrogen with which she was filled caught fire and destroyed this dirigible at Lakehurst, N. J. Hence, hydrogen is dangerous to use for filling dirigibles, especially if the dirigible were to be used for military purposes. *Helium* is a gas which is twice as dense as hydrogen, but it does not burn. Its so-called lifting power is equal to 1.11 gm. per liter (1.29 − 0.18). Hence it is 93% as efficient as hydrogen. When the United States secured the ill-fated *Los Angeles,*

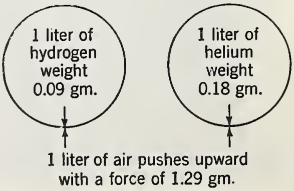

1 liter of hydrogen weight 0.09 gm.
1 liter of helium weight 0.18 gm.
1 liter of air pushes upward with a force of 1.29 gm.

FIG. 109. The so-called lifting force of helium is less than 93% that of hydrogen.

she was filled with helium gas at the hangar at Lakehurst upon her arrival from Germany.

Before World War I, the price of helium was about $1700 per quart. When its importance as a war material was realized, engineers began a world-wide search for a more abundant supply. The natural gas from certain wells in Oklahoma and Texas was found to contain 1 or 2% of helium. Liquid air machines are used to separate the helium from the natural gas. The mixture is cooled and compressed until everything but the helium liquefies. The helium gas is then drawn off and forced into steel cylinders whence it is shipped to the United States Naval Field at Lakehurst. The cost of producing helium in this manner is said to be about one cent per cu. ft.

*Airships*, or *dirigibles*, are balloons fitted with steering devices and propellers. Gasoline engines aggregating 3000 to 5000 horsepower are used to drive the propellers of huge military dirigibles, some of which measure nearly 700 ft. in length. (See Fig. 110.) The high-school pupil can form a fairly good idea of the enormous size of such dirigibles, if he stops to consider that the biggest ones are longer than two football fields placed end to end, taller than a five-story school building, and broad enough to accommodate sixteen automobiles abreast.

**91. How high does a balloon rise?** Since air is very compressible, the layers near the surface of the earth are compressed by the weight of the air they sustain, and their density is correspondingly increased. As a balloon rises, it enters an atmosphere that is constantly growing rarer, and the buoyant force of the air is decreasing. A balloon will continue to rise until the weight of the balloon and its contents exactly equals the weight of the air displaced. Water is often carried as ballast, and released if the balloonist wishes to go higher. He may descend by releasing some of the gas. If balloons are filled entirely full before starting, the unbalanced expansive force might burst the gas-bag when the balloon rises into a rarer atmosphere.

*Pictures, Inc.*

FIG. 110. The Graf Zeppelin circling the Capitol Building in Washington. This dirigible made a flight around the world in 21 da., 7 hr., and 34 min.

**★92. How are gas pressures measured?** We buy gas at a certain price per 1000 cu. ft. Since the density of that gas varies so much with the pressure it sustains, it makes a decided difference whether our gas is measured for us at a low pressure or a high pressure. If we put enough water into a bent tube like that shown in Fig. 111 to stand about 4 in. high in each arm, and attach it to a gas jet, we find that the water will rise a few inches higher in the open arm when the gas cock is

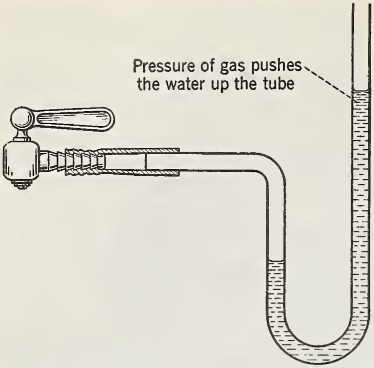

Pressure of gas pushes the water up the tube

Fig. 111. The open manometer may be used to measure gas pressures.

opened. The difference in height enables us to measure the amount by which the gas pressure exceeds the atmospheric pressure.

Mercury may be used in such a manometer. For high pressures a *closed manometer*, Fig. 112, may be used. A spring gauge, similar to the one shown in Fig. 113, is also used. Most gauges show a reading of zero at normal atmospheric pressure. Hence the actual pressure, or the *absolute* pressure, equals the *gauge* pressure plus 14.7 lb. per sq. in. Manometers and gauges may also be used to measure reduced pressures. Engineers speak of a "27-in. vacuum" or a "28-in. vacuum" in referring to reduced pressures. A "28-in. vacuum" means that the pressure is 28 in. less than one atmosphere, which is 30 inches. The gas in a "28-in. vacuum" exerts a pressure of just 2 inches of mercury.

**93. How does the gas meter work?** The gas meter is a metal box divided into four compartments by flexible diaphragms. By a slide valve these compartments are alternately connected with the city supply and with the pipe to the consumer. While the gas in two of the compartments is being used, the other two gas compartments are being filled. (See Fig. 114.) The movement of the diaphragms not only operates the slide valve but it also controls a clockwork device which records the number of cubic feet of gas that

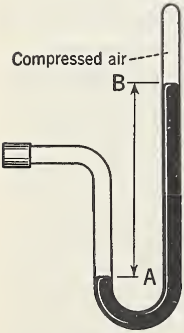

Compressed air
B
A

Fig. 112. The closed manometer is used to measure high pressures.

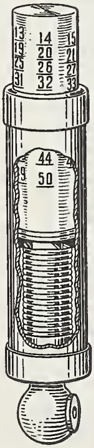

13
14
15
19
20
21
25
26
27
31
32
33
44
50

Fig. 113. The spring gauge is used to measure air pressures.

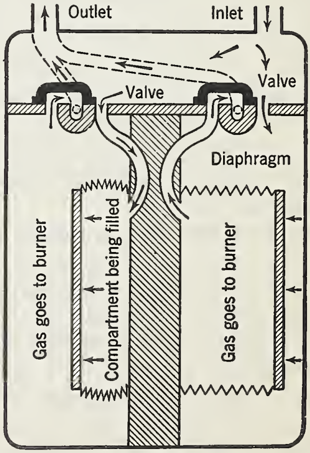

Outlet
Inlet
Valve
Valve
Diaphragm
Gas goes to burner
Compartment being filled
Gas goes to burner

Fig. 114. The gas meter is used to measure gas consumption in cubic feet.

passes through the meter. Fig. 115 shows the dials of a gas meter. An employee of the company reads the meter monthly and determines the amount of gas used each month by subtracting the previous reading from the present one. The dials as shown in Fig. 115 indicate 59,300 cu. ft. When the needle stands between two numbers, as on the left-hand dial, the lower number is taken as the reading.

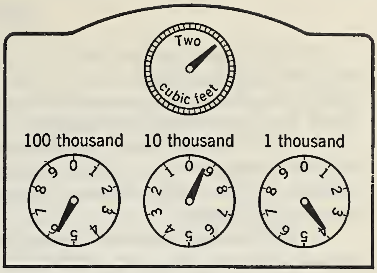


Fig. 115. Dials of a gas meter.

## Summary

Air has weight. 1 liter of dry air at S.T.P. weighs 1.293 gm. Air also exerts pressure. At sea level the pressure is 14.7 lb. per sq. in.

The rise of liquids in exhausted tubes is caused by air pressure. Torricelli showed that air pressure supports a column of mercury 76 cm. high. Pascal showed that air pressure decreases as the elevation is increased.

A barometer is an instrument used to measure atmospheric pressure. It is used to measure altitudes and in weather forecasting. A rising barometer indicates fair weather. A falling barometer indicates an approaching storm. A steady barometer indicates settled weather.

Unlike liquids, gases placed in a container expand and fill the container. Gases also differ from liquids in that they are easily compressed.

Robert Boyle found that at constant temperature a given volume of dry gas varies inversely as the pressure sustained by it. The density of a gas increases with increased pressure.

Archimedes' principle applies to gases. The buoyant force a gas exerts is equal to the weight of the gas displaced.

Compressed air is used in pneumatic tires, diving bells, air brakes, riveters, and drills.

Exhaust pumps are used in making vacuum bottles, electric and radio bulbs, X-ray tubes, and in ventilating systems. Some types of water pumps and the siphon depend upon the pressure of the air for their operation.

*How many of the following terms can you define or explain? (Do not guess.)*

Atmospheric
Magdeburg hemispheres
Mercury barometer
Aneroid barometer
Barograph
Altimeter
Terrain clearance indicator
Isobar
Isotherm
Cyclone
Caisson
Anti-cyclone
Stratosphere
Troposphere
Compressibility
Aspirator
Dehydrated
Cartesian diver
Helium
Hydrogen
Standard temperature
Standard pressure
Atomizer
Siphon

## QUESTIONS

1. Why does a balloon rise? To what height will a balloon rise?

2. In a book that appeared during World War I, the following statement was made: "The Germans have discovered a gas which has several times the lifting power of hydrogen." Does the statement appear reasonable? Explain.

3. Why do both valves of a pump open upward? Why do they open alternately?

4. Water is often poured into the top of a lift pump to aid in starting it. Explain how it helps. (This operation is called "priming" the pump.)

5. Take a reading of your gas meter on the same day that it is read by the company employee. Take a second reading a month later, and calculate your gas bill.

6. A pipe is sometimes fitted to the water pipe near the faucet, as shown in Fig. 116. How does such a pipe, which contains air, keep the water from "pounding" when the water is turned off suddenly?

7. To what height must the siphon shown in Fig. 117 be filled before it begins to flow? How long will it continue to flow? To what height must the water rise before it starts flowing a second time? (Some springs which flow for a given period and then stop flowing for a few weeks or months are believed to have siphon-shaped outlets. Make a sketch diagram to show how such an intermittent spring would work.)

8. Will a siphon flow if the short arm is more than 34 ft. long? Give a reason for your answer. Will it flow if the long arm is more than 34 ft.?

9. Will a siphon flow in a vacuum? Explain.

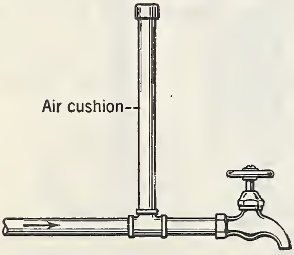


FIG. 116. The air cushion in the vertical pipe prevents "pounding."

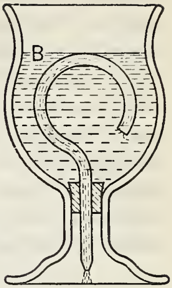


FIG. 117. The intermittent siphon.

10. The aspirating siphon is used with corrosive liquids. Study Fig. 118, and tell how you would fill such a siphon with liquid to start its action.

11. What is the purpose of the trap in a sink? (See Fig. 119.) Is it a siphon? If not, what prevents it from acting as a siphon?

12. Can one siphon water from the bottom of a boat or canoe that is floating in the water? Explain.

13. Is it possible to siphon water from the bottom of a boat that has been drawn up on the shore at the edge of a lake?

14. Why is a small rubber balloon filled with hydrogen likely to burst after it has risen to some height?

15. Would you use a force pump or a lift pump if you wished to pump water to the top of a 40-story building? Why?

16. Explain why a balloon is only partly inflated before a flight is begun.

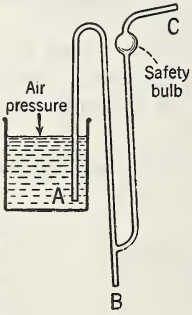


FIG. 118. The aspirating siphon.

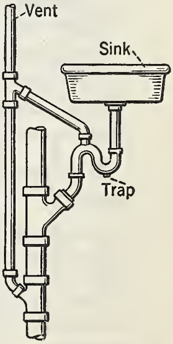


FIG. 119. Trap for sinks.

## PROBLEMS

### Group A

1. A lift pump is to be used for pumping gasoline, sp. wt. 0.7. How high can the gasoline be pumped by a pump that could lift water to a height of 28 ft.?

2. Coal gas is sometimes used for filling balloons. It weighs 0.75 gm. per liter. What is its lifting force per cu. m.?

3. If a barometer reads 24 in. of mercury at Denver, what is the greatest elevation over which water could be siphoned in that city? In how deep a well could a lift pump be used?

4. A tire gauge used to test an automobile tire shows a reading of 30 lb. What is the absolute pressure? What would be the weight of 1 liter of air in the tire?

### Group B

5. If the total weight of a balloon is 1000 lb., what must be its volume in cu. ft., if it is filled with hydrogen?

6. What volume must the balloon of Problem 5 have if it is filled with helium?

7. What volume in cu. m. must a balloon filled with hydrogen have if the balloon is to carry a gross load of 5000 kgm.? If it is to carry 5000 lb.?

8. A tire gauge reads 35 lb./sq. in. when used to test an automobile tire. If the tire holds 1200 cu. in. of air at this pressure, what volume will the air occupy after a blowout of the tire?

# Unit Two

# *Molecular Physics*

## Preview

SOME OF US ENJOY WATCHING A MAGICIAN. WE PAY HIM to fool our eyes. But, strange as it seems and despite the fact that it is so easy to deceive the eye, we are likely to say: "You can't fool me. I saw it." We find it hard, too, to believe in things that we cannot see.

In this unit we shall discuss particles that are so small that it would take at least a thousand of them laid side by side to make a line long enough to be seen by the best microscope. How do we know that such tiny particles, which we call molecules, exist? No one has seen them, but we know how they act and the effects they produce. They have been weighed and measured. These tiny molecules are the *invisible* players in the game which we study in this unit.

In many solids we find that the molecules are so firmly attached to other molecules that it is difficult to detach them. They escape from gases and some liquids so readily that they seem to be repelled by some strong force. When we smell camphor gum, the molecules escaping from the surface of the camphor come into contact with our olfactory nerves. Our nose tells us that some tiny particles are entering our nostrils. We must learn not to depend entirely upon our eyes, but to keep other avenues of learning open.

The red blood cells acted as delivery boys and carried their packets of oxygen to the cells long years before anyone ever saw them with the aid of a microscope. Even if it does take about thirty-five hundred of them laid side by side to make a line an inch long, yet they are large enough to carry the oxygen molecules. Some of the things that we learn in this unit are based upon theory, but scientists are almost as firmly convinced of the truth of the theory as they are of some demonstrable facts.

If you find it hard to stretch your imagination far enough to accept the molecular theory of matter, you may find it even harder to accept the belief that molecules are made up of even smaller particles called atoms. The atom is the unit with which the chemist deals.

At the present time we no longer believe that John Dalton was correct when he assumed that atoms are indivisible. Some of them explode spontaneously; physicists have knocked some of them to pieces by bombarding them in atom-smashing machines. A study of the fragments and the energy they release or absorb is included in the science of radio-activity. The electron is a most fascinating unit of matter. A stream of them forms an electric current. They flow through the detector tube of your radio and make reception possible. With the end of World War II, we may find them more largely used in television. They play their part in X-ray machines, and they are useful in the operation of *radar*. Many colleges and universities now give courses in *electronics*.

# *Molecules — Their Behavior*

## 1. Molecular Motions

**94. What is the kinetic theory of matter?** We have learned that all matter seems to be made up of exceedingly small particles called molecules. In gases especially, we know that the molecules are not relatively near neighbors. In liquids and solids, they are more closely crowded, but in all cases there is ample room between adjacent molecules to permit the molecules to move freely. The Greek word *kinein* means *to move*. Our English word *kinetic* is derived from the Greek word. Hence, *the kinetic theory of matter assumes that the molecules of all matter are in constant motion.* The rate and nature of such motion depend upon the nature of the substance, its state, and its temperature. There are many evidences of the correctness of the kinetic theory.

**95. What is Brownian motion?** By the use of the ultramicroscope we can see how particles which are suspended in a liquid are driven forward and backward, or up and down, in ceaseless motion, by the impacts which they receive from moving molecules in the liquid. Try to imagine a soccer game in which you can see the ball but not the players. One player drives the ball across the field in one direction, another drives it back at a different angle, and then a third player drives the ball in a still different direction. In a similar manner a liquid molecule in motion collides with the tiny particle which you are watching. You see it driven forward by the force of the impact. Then, after it has traveled a short distance, it may be struck by another molecule moving in a different direction and have its path changed again. Thus we have the ceaseless dance of such particles as they are driven hither

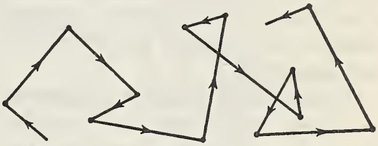


FIG. 120. The particle is driven hither and thither by the impacts of moving molecules.

### Vocabulary

KINETIC, moving.
DIFFUSION, intermingling without regard to weight.
OSMOSIS, diffusion through membranes.
SURFACE TENSION, the contractile property of liquid films.
ADSORPTION, the condensation of gases on the surfaces of a solid.
ABSORB, to suck up, imbibe, or take in.
OLFACTORY, pertaining to the sense of smell.
ULTRAMICROSCOPE, an instrument used to see light reflected from particles too small to be seen by an ordinary microscope.
EVAPORATION, changing from a liquid to a gas or vapor.
MENISCUS, curved part of a liquid surface.

and thither. Because such motion was discovered by Robert Brown, a Scottish botanist, the name *Brownian movement* is given to this phenomenon. Minute oil drops suspended in air undergo the same zigzag movement as they are driven about by rapidly moving air molecules. Fig. 120 represents a path that might be followed by such a particle.

## 2. Molecular Motions in Gases

**96. Gases expand.** If a gas cock is left open, in a few minutes the odor of gas may be detected in all parts of the room. If we unstopper a small bottle of chlorine gas in a large vessel of air, the yellowish green gas may be seen expanding and mixing with the air in the vessel. The gas molecules move rapidly in all directions until they become thoroughly mixed with the air molecules. Evidently the molecules of these gases are in very rapid motion. Air from the bell glass, Fig. 83, expands instantly and fills the vacuum formed beneath the rising piston of the air pump. If the molecules of gases were not in constant motion, it would be impossible to produce a vacuum with an air pump. The expansion of gases furnishes one proof of the motion of their molecules.

**97. Gases exert pressure.** Pneumatic tires may burst from the pressure which the air inside exerts on the walls of the tire. This pressure is due to the constant bombardment of the tires by billions of moving molecules. If we pump three atmospheres into the space formerly occupied by one atmosphere, there will be three times as many molecules bombarding the walls of the container, and the pressure will be three times as great. From Fig. 121 we see that tripling the number of molecules in a given space will triple the pressure because there will be three times as many impacts against the walls as before. An automobile driver uses a small pressure gauge to measure the force exerted by the molecules upon each square inch of the inflated tire. By Pascal's law, the pressure is transmitted equally in all directions. If one spot in the tire is especially weak, a "blow-out" is likely to occur. All the devices which utilize compressed air afford examples of gas pressure due to molecular motion. Steam in boilers often exerts a pressure of 200 lb. or more per sq. in. In this case it is also evident that the molecules are widely separated when compared with the diameters of the molecules themselves, for the water formed when steam condenses occupies about $\frac{1}{1700}$ the volume of the original steam. The high temperature increases the velocity of the steam molecules, and the rapidly moving molecules exert great pressure.

**98. Diffusion of gases shows that molecules of gases are in motion.** Hydrochloric acid is a water solution of a dense gas, hydrogen chloride; aqua am-

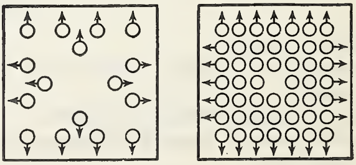


Fig. 121. Increasing the number of molecules in a container increases the pressure.

monia is a water solution of a light gas, ammonia. When these two gases unite, they form a cloud of fine white particles. Suppose that we put a couple of drops of hydrochloric acid in a warm bottle, an equal amount of aqua ammonia in a second bottle, cover both with glass plates, and then invert the bottle containing ammonia over the acid bottle, as shown in Fig. 122. After the bottles have stood for a minute or two, a vigorous action may be observed when we remove the glass plates. The light ammonia gas moves *downward* and mixes with the dense hydrogen chloride, and vice versa. The student will note that the intermingling is apparently contradictory to the laws of weight. Other gases may be used, and they behave in the same manner. For example, carbon dioxide is about 22 times as dense as hydrogen, but if bottles of these gases are placed mouth to mouth, the hydrogen gas *above* and the carbon dioxide *below*, some of the molecules of the dense gas will move *upward* and mix with the hydrogen and some of the light hydrogen molecules will move *downward* and mix with the carbon dioxide. If the denser gas had been placed at the top, we could explain this phenomenon by the laws of weight, but since the gases moved in apparent violation of the laws of weight, it is quite evident that the molecules of gases are in motion. *Such intermingling of gases without regard to weight is called diffusion.*

**99. Gases diffuse through porous solids.** In the apparatus shown in Fig. 123, an unglazed earthenware cup is closed with a rubber stopper carrying a glass tube which dips into some colored liquid. When a beaker is inverted over the cup and illuminating gas is led into the beaker, air begins to bubble out through the liquid. This experiment shows that gases *diffuse* through a porous solid. It also shows that the lighter molecules of illuminating gas move faster than the denser molecules in the air. If a dense gas such as carbon dioxide is led into the beaker, molecules from the air flow out through the porous cup faster than the carbon dioxide molecules enter. This reduces the pressure inside the cup and the colored liquid rises in the tube. Such diffusion always takes place more rapidly from a less dense to a more dense medium.

The importance of such *diffusion of gases through a plant or animal membrane*, can hardly be overestimated. The process is called *osmosis*. In ordinary breathing, the oxygen of the air passes through the walls of the capillaries in the lungs and enters the blood. It passes through the cell walls in the same manner. Osmosis also occurs in plant tissues. Without osmosis, plant and animal life would cease to exist. By osmosis, carbon dioxide enters the cells in the leaves of plants.

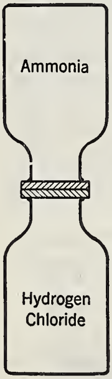


Fig. 122. Gases mix by diffusion of the moving molecules.

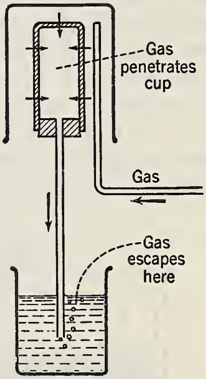


Fig. 123. Gases readily diffuse through porous solids. They also diffuse through membranes.

## 3. Molecular Motion in Liquids

**100. Why do liquids evaporate?** Everyone knows that water left standing in an open vessel soon disappears by evaporation. It seems to be quite impossible to explain such disappearance of liquids, unless we assume that the molecules of the liquid are in motion. In Fig. 124, we may picture what we believe to be constantly taking place in a liquid. The molecules move in all directions. Only those moving upward can escape into the air. Those that collide with air molecules may rebound into the liquid again. Exhausting the air above the liquid prevents such collisions, and furnishes an explanation for the fact that liquids evaporate more rapidly in a vacuum.

Visitors at the Century of Progress Exhibition saw small steel balls thrown about violently by the bombardment of rapidly moving molecules at the surface of heated mercury.

**101. Diffusion of liquids is slower than that of gases.** Let us pour into a tall cylinder enough concentrated copper sulfate solution to form a layer of blue liquid two or three inches deep. Float a flat cork on the surface of the copper sulfate solution. We can then pour water carefully through a funnel tube on top of the cork so that it will spread out over the surface of the blue liquid, forming two distinct layers, since the water is much less dense than the solution of copper sulfate. (See Fig. 125.)

After this cylinder stands a few days, the line of demarcation becomes quite irregular. Some of the blue solution moves upward and mixes with the water above, and some of the water molecules move downward into the copper sulfate solution. This experiment shows that diffusion also occurs in liquids. It may require weeks or months before the diffusion is complete, whereas the diffusion between the gases discussed in Section 98 was complete in a few minutes. This experiment shows that the molecules of liquids are in motion, but that they move much more slowly than the molecules of gases.

**102. Does osmosis occur in liquids?** The apparatus shown in Fig. 126 may be used to show that liquids diffuse through membranes. The diffusion apparatus, and the attached tube are partly filled with a colored sugar solu-

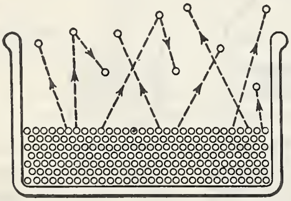


FIG. 124. Moving molecules escape at the surface of a liquid.

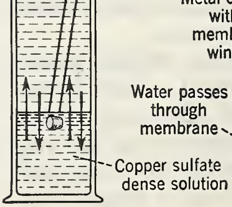


FIG. 125. Liquids diffuse more slowly than gases do.

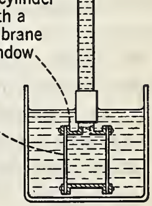

Sugar solution
Metal cylinder with a membrane window
Water passes through membrane

FIG. 126. Liquids pass through membranes by osmosis.

tion of 1% or 2% strength. The shell is then immersed in a vessel of water. In a few minutes the liquid begins to rise in the tube, and by the following day it will probably have reached a height of several feet. The light water molecules move much more rapidly than the sugar molecules, and for that reason their penetrating power is greater. In the osmosis of liquids, the *diffusion takes place from the less dense to the more dense liquid.* The pressure produced by the osmosis of liquids may equal several atmospheres.

Osmosis of liquids is quite as important as that of gases. The purpose of digestion is to render the food sufficiently fluid to be absorbed by osmosis. Each cell receives its nourishment by osmosis through the cell wall. The mineral matter in the soil dissolves in the water and enters the root hairs of plants by diffusion. Thus plants depend upon osmosis for nourishment.

Oysters are wrinkled when removed from sea water. They are "fattened" by floating them in fresh water. The osmosis is inward and the body wall is distended by the *osmotic pressure.* To prevent contamination with typhoid bacteria in polluted streams, the government now decides where oysters may be fattened. The entire process is becoming less and less common.

## 4. Molecular Motion in Solids

**103. Solids evaporate.** The fact that solids evaporate is not so well known, but a little thought must convince us that solids do evaporate, although in most cases very slowly. A piece of musk will give off enough vapor to be perceived in any part of the room. A lump of camphor gum, or a crystal of iodine, will disappear in a short time by evaporation. Moth balls evaporate completely in time. Snow and ice evaporate quite readily. They disappear when it is too cold for them to melt. It is probable that many other solids evaporate, but so slowly in many cases that it is hardly noticeable. Thus the evaporation of solids furnishes evidence that their molecules are in motion. It is difficult to see how any solid can have an odor unless its molecules escape by evaporation.

**104. Diffusion of solids is very slow.** If a lead plate and one of gold are left in close contact for a long time, particles of gold may be detected throughout the lead, showing that solids diffuse. The action is so slow that months are needed to produce even a slight diffusion. Other solids show a similar effect if the temperature is increased a few hundred degrees. From the evaporation and diffusion of solids, it is evident that molecular motion exists, even in compact, dense solids.

## 5. Molecular Forces

**105. There are molecular forces in solids.** Since there is so much evidence in support of the kinetic theory of matter, the student probably wonders why all substances do not evaporate rapidly and expand indefinitely. Instead, we know that many solids have great tensile strength, and that enormous forces are required to pull them apart. In spite of the molecular motion, there seems to be a strong force binding together the molecules of such tenacious solids. *This force of attraction between like molecules is called cohesion.*

*Unlike* molecules sometimes *adhere* to one another strongly. Tar sticks to our shoes, glue sticks to wood, and the dextrine on a postage stamp makes it adhere to an envelope. When we write on the blackboard some of the particles of the crayon adhere to the board. Writing with a "lead" pencil would be impossible if the molecules of the graphite of which the pencil is made did not adhere to the paper more strongly than they stick together. *The force of attraction between unlike molecules is called adhesion.*

**106. Compare solids, liquids, and gases.** Generally, the force of cohesion in solids is very great. The moving molecules are so firmly held by this force that they probably oscillate about fixed points, and do not change their relative positions to any marked degree.

In such liquids as tar and molasses, it is evident that the force of cohesion is considerable. In such mobile liquids as water and alcohol, the cohesion is much less, although still measurable. While in liquids the force of attraction between molecules exceeds the effect due to molecular velocities, yet the difference is so small that liquid molecules readily slide over one another; thus the liquid takes the shape of the container.

In gases, cohesion is very feeble, and molecular motion so evident that the molecules of gases actually *appear* to repel one another. The force of cohesion is so small that it does not prevent gases from expanding indefinitely.

It seems apparent that the state of matter depends upon the balance between molecular forces and molecular velocities. In a bar of steel, cohesion is exceedingly great and molecular velocity seems small. If we warm that piece of steel, its molecules move faster, and its strength is diminished. If we continue to raise its temperature, a point is finally reached where the steel becomes liquid. Its molecules then slide over one another like those of water. At still higher temperatures, steel becomes a vapor, and has the properties of gases.

**107. Elasticity depends upon cohesion.** From the preceding section it is easy to see that the tenacity, or tensile strength, of a substance depends upon the cohesion of its molecules. Several other special properties of matter, such as ductility, hardness, and malleability, depend upon cohesion. The elasticity of solids is also dependent upon this force.

It takes a certain amount of force to stretch a rubber band. When the distorting force is removed, the rubber band tends to resume its original length. Such a band is said to be *elastic*, and that type of elasticity which is exemplified by the stretching of a rubber band is called elasticity of *extension* or *traction.* Engineers use the term "stress" in speaking of a force which acts upon a body and tends to distort it. The change produced or the distortion is called "strain." If we squeeze a tennis ball, it becomes distorted, but it tends to recover its original form and size when the stress is removed. This is an example of elasticity of *compression.* A golf ball struck by a club is compressed before it begins its flight. The twisting of a coiled spring is an example of elasticity of *torsion.* The elasticity of *flexion* or *flexure* is exemplified by the bending of a strip of steel. In all these cases the body tends to resume its original form when the stress is removed.

**★108. How is elasticity measured?** Usually when one speaks of an elastic object, he means one which is easily distorted, such as rubber. Engineers use the term "elasticity" in a different sense. Steel is said to be highly elastic, because it requires a great force to cause its deformation. Steel has a high *elastic constant.*

Suppose that we have two wires of different material, but of the same cross-sectional area. If it requires twice as much stress to stretch the first a certain distance as it does to stretch the second the same distance, the former has an elastic constant twice as high as the latter. In this sense steel is the most elastic substance known. Rubber has a very low elastic constant.

**109. What is perfect elasticity?** If we stretch a coiled spring, it *may* return exactly to its original form after the removal of the stress. (See Fig. 127.) If it does, it is said to be *perfectly elastic.* If we stretch such a spring too far, it remains permanently distorted. We have exceeded its *elastic limit.* Every material has a certain range of perfect elasticity through which it may be distorted before its elastic limit is reached. For example, it takes a great force to stretch a steel wire, but it cannot be stretched very far without becoming permanently distorted. Its *elastic constant* is high, but its *elastic limit* is low.

Liquids are perfectly elastic and they have a high elastic constant. Gases have a low elastic constant, as we find if we consider Boyle's law. They are, however, perfectly elastic. With both liquids and gases, we are concerned with elasticity of compression *only.* Within the limits of perfect elasticity, the elastic constant of any substance equals $\frac{\text{stress}}{\text{strain}}$. *Stress is the acting force and strain is the change produced.*

**110. What is the law of rebound?** If we throw an elastic object against a hard surface, it rebounds. As a batted ball comes toward him, the shortstop on a baseball team must be able to judge the angle which it will make with the earth, the point at which it will strike the ground, and the angle at which it will rebound. If his judgment is accurate, he can then place his hands in position to catch the ball as it rebounds. In Fig. 129 let the horizontal line represent the ground and $O$ the point at which the ball hits the ground. Suppose that we erect a perpendicular $OC$ at $O$. The line $AO$ shows the path of the ball, and $OB$ the line along which

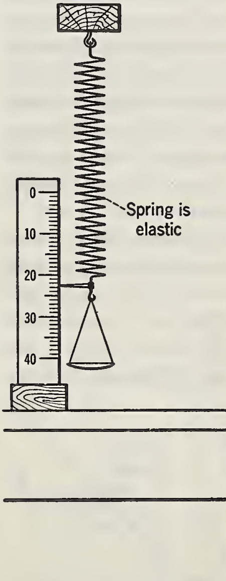


FIG. 127. Elasticity of extension in a coiled spring.

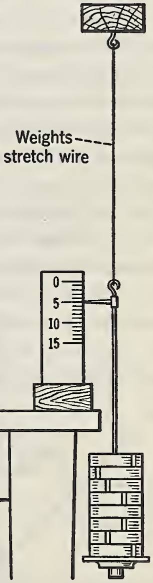


FIG. 128. Testing the tensile strength of a wire.

it rebounds. If the ball is perfectly elastic and the surface hard, the ball will rebound so that the angle $BOC$, or the angle which the line of rebound makes with the perpendicular, is exactly equal to the angle $AOC$, or the angle that the line along which the ball was batted makes with the perpendicular. *The angle of rebound, BOC, is equal to the angle of incidence, AOC.* In tennis, basketball, billiards, etc., the player is constantly making use of this *law of rebound.*

When a ball that is not perfectly elastic, a dead tennis ball for example, is driven against a hard surface, the angle of rebound, $ROC$, is greater than the angle of incidence. Uneven surfaces and balls that have lost some of their elasticity are responsible for many errors in baseball and tennis.

There is one exception to the law of rebound. A ball spinning on its axis as it moves does not rebound as shown in Fig. 129. A tennis ball that is "cut" to make it rotate is harder to handle, since the player who receives cannot judge the rebound. Of course, a ball that is spinning does not travel along a straight line, but along a curve.

**111. What is Hooke's law?** If we fasten one end of a wire to a beam, as in Fig. 128, and add weights to the hanger attached to the other end, the wire will be gradually stretched as weights are added one by one. Suppose that we find that a weight of 100 gm. stretches the wire 1 mm.; then 200 gm. will stretch the wire 2 mm.; 300 gm., 3 mm.; and so on, until the elastic limit is reached. By such methods Hooke found that distortion is proportional to the distorting force, or, in general, *distortions of elastic material are directly proportional to the distorting force, provided the elastic limit is not exceeded.* HOOKE'S LAW may be briefly stated as follows: *Within the limits of perfect elasticity, strain is directly proportional to stress.* The spring balance is a common example of this law, since the 1-oz. divisions are equidistant.

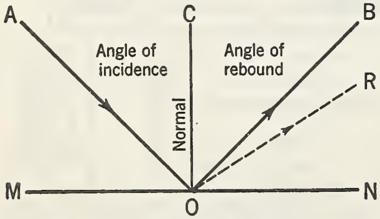


FIG. 129. Angle of incidence and angle of rebound are equal.

**112. How can we find strength of materials?** It is very important for builders to know the coefficient of elasticity of structural materials. It is just as essential for engineers to know the breaking strength of the materials which they use. In physical testing laboratories, strong machines are used to measure the strength of materials. Such machines test the tensile strength of cables, ropes, wires, belts, etc. Tests are made of the compression strength of materials used for piers, pillars, posts, and foundations, which must not be crushed by the load which they are required to sustain. The propeller shaft of a steamship and the power shaft of an automobile must transmit power without the twisting of the shafts themselves. A General Motors exhibit at the Century of Progress Exhibition enabled one to measure in millionths of an inch the amount he could bend a piece of standard steel rail by pressure with his fingers. Several types of beams

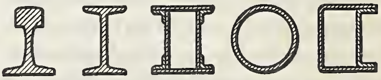


FIG. 130. T-rail and beams of various types in cross-section.

have been designed to give great strength without undue increase in weight. Fig. 130 shows some of the types that are very much used by structural engineers.

When designing machines or structures of any kind, engineers always plan to use materials heavy enough to carry several times the load that is likely to be put upon them. This gives a *factor of safety*, for it provides for flaws in the material and for temporary overloading. A bridge which is made of material heavy enough to carry 50 tons is said to have a safety factor of 5, if its load is limited to a capacity of only 10 tons. Six cables were used to lift the elevators to the top of the 624-ft. observation tower of the Sky Ride in Chicago, although one cable was strong enough to carry the load. That furnished a safety factor of six.

**113. There are molecular forces in liquids.** If we stick our finger into thick molasses and then withdraw it, we are conscious of a certain amount of force needed to pull apart the molecules of the molasses. By use of the following experiment, it may be shown that some force is necessary to overcome the cohesion of water molecules. Let us attach a glass plate to one pan of a balance and counterpoise it. Next we shall place a jar of water under the glass plate so that the lower surface of the plate just touches the surface of the water. We may now add several small weights in order to lift the plate. (See Fig. 131.) Since the plate is wet when pulled away, the additional weights must have been used to tear the water molecules apart. The adhesion of the water molecules to the glass is greater than their cohesion for one another; hence water wets glass.

If mercury had been used instead of water, the glass would not have been wet by the mercury, since the cohesion of mercury molecules is greater than their adhesion to glass. For the same reason, mercury does not wet the finger when it is dipped into a bowl of mercury. The force of cohesion varies in different liquids. It is less than in solids, but it is fairly strong in some *viscous* liquids.

**114. What are surface tension and liquid films?** Nearly everyone has seen someone float a small sewing needle or a safety-razor blade on the surface of a glass of water. The needle is more than seven times as dense as the water. A careful examination of the water surface shows that the needle floats in a little hollow in the water surface. *The water behaves as if a thin elastic film or membrane had been stretched over its surface.* This property of liquids is called *surface tension.* The weight of the needle is not great enough to break this liquid film. A wet needle cannot be floated in this manner; hence this experiment is more easily performed if the needle is first covered with a film of oil.

Small insects run around over the surface of the water, since their weight is not great enough to break the surface

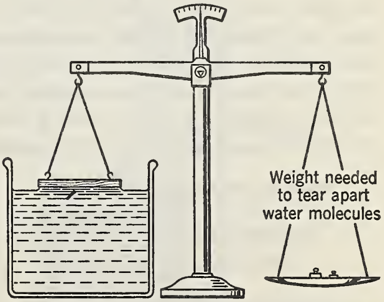


Fig. 131. Cohesion of water molecules is measurable.

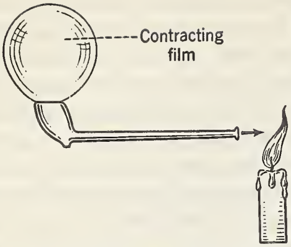


FIG. 132. Film contracts and expels part of the air.

film. All liquids are like water in this respect. In alcohol, the film is not so strong as in water. Many oils, too, have a weaker film, but they are much more *viscous*. There is more friction within the liquid itself. Hence it pours slowly. Adding soap to the water increases the *viscosity*. Engineers test the viscosity of lubricating oils by counting the number of drops which will pass through a tiny opening in one minute. For comparison, several glass tubes may be filled with oils of different viscosity. Their relative viscosities are compared by noting the relative times needed for steel balls of equal weight to fall through the oils in the tubes.

**115. Liquid films are elastic.** If we blow a soap bubble and then remove the pipe from the mouth, the bubble slowly contracts, forcing the air out of the pipe-stem. (See Fig. 132.) A film of soap will slide the looped wire along the frame of Fig. 133 as it contracts. When we dip a wire ring containing a loop of thread, Fig. 134*A*, into a dish of strong soapsuds, a film is formed across the ring. If we break the film inside the loop with a hot wire, the unbroken film outside the loop contracts and pulls the thread into the form of a circle, as in Fig. 134*B*. These experiments show that *the surface films of liquids are elastic*. Since this film contracts to make the surface as small as possible, the tendency of liquid films to contract is often called the *surface tension of liquids*.

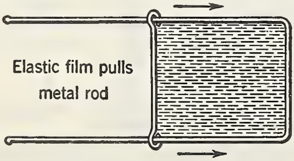


FIG. 133. Liquid film is elastic and contractile.

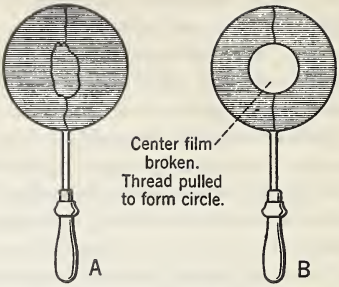


FIG. 134. *A*. Soap film is formed. *B*. Soap film contracts and pulls loop of thread into circle.

Reference to Fig. 135 aids in the explanation of surface tension. A molecule at *A* is attracted equally in all directions by the cohesion of the surrounding molecules. A molecule at *B* is attracted laterally and downward, but not in an upward direction. Thus there is exerted upon the surface molecules an unbalanced force tending to pull them toward the interior of the liquid. This unbalanced, contractile force causes the surface to act like an elastic membrane.

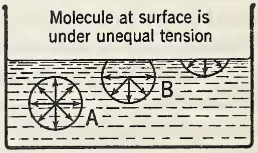


FIG. 135. Any molecule at the surface is under uneven tension.

**116. What is the shape of liquid surfaces?** A careful examination of the surface of the water in a glass container shows that it is not *exactly* level but that it is *slightly concave*. The edge of the surface where it comes into contact with the glass is lifted a little above the general level. (See Fig. 136 *A*.) This crescent-shaped surface of a liquid column is called the *meniscus*. In reading the height of the water surface in a graduated glass cylinder, we read to the *lower part* of the meniscus, since the actual volume of liquid lifted above this level is small. The reason for the lifting of the water at the edge is explained by the fact that the *adhesion* of the water for the glass is greater than the *cohesion* between the water molecules.

When mercury is used instead of water, the edges of the liquid are depressed and the surface is *slightly convex*. In this case the cohesion between the mercury molecules is greater than their adhesion for the glass. (See Fig. 136*B*.) In reading the height of a mercury column, one reads to the *top* of the meniscus.

**117. What shape does a free liquid assume?** When we speak of a free liquid, we refer to a liquid that is not subjected to any force or pressure. A little water poured upon the floor is not a free liquid. Under the influence of gravity, the water spreads out in all directions, since its molecules slide over one another readily. Raindrops are nearly spherical; they are common examples of free liquid. If we fill a glass cylinder half full of water, and then float a layer of alcohol on the surface of the water, we can lower a drop of oil into the liquid and practically nullify the force of gravity. The oil is denser than the alcohol, but not so dense as the water. Hence it floats in the mixture. *Its shape is spherical.* (See Fig. 137.)

Suppose that one is given a cubic inch of some plastic wax and told to fashion it into such a shape that it will have the smallest surface area that is possible. By geometry, one finds that a sphere has a smaller surface area for a given volume than any other geometrical figure. As the film on the surface of a free liquid contracts, it pulls the liquid into the shape of a sphere, reducing the surface area to a minimum. Mercury spilled on a table breaks up into small drops, since the effect of gravity is small compared to the cohesive force of the molecules of mercury. Larger globules are distinctly flattened.

**118. What is capillarity?** In Section 31 the statement was made that liquids

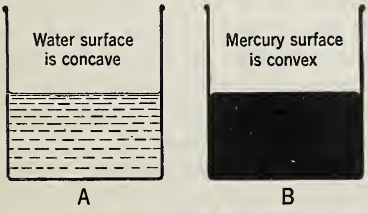


FIG. 136. *A*. Liquids which wet the surface of their containers have concave surfaces. *B*. Liquids that do not wet vessels have convex surfaces.

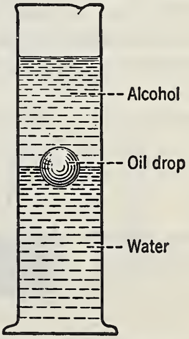


FIG. 137. A liquid that is free from a distorting force takes a spherical shape.

in communicating vessels seek the same level. The statement is not rigorously exact, and a correction must be made for communicating tubes of small diameter. Experiment shows that water does not stand at the same level in communicating tubes of varying diameters, but rises higher in tubes of small diameter, Fig. 138*A*. When mercury is used, the depression is greater in tubes of small diameter, Fig. 138*B*. This elevation, or depression, of liquids in *capillary* (hair-like) tubes is known as *capillarity.*

Capillarity really depends upon adhesion and surface tension. The adhesion of water for the glass causes the surface of the water to become *concave.* Surface tension tends to decrease the surface area, or to flatten it by contraction. The two forces working together lift the liquid above the surrounding level. The height to which the liquid will be lifted depends upon its weight and the strength of the liquid film. In liquids like mercury, cohesion makes the surface *convex,* and surface tension, by tending to flatten it, produces depression of the liquid in the tube.

**119. What are the laws of capillarity?** Several laws that apply to capillarity have been verified by experiment: (*a*) *Liquids rise in capillary tubes if they wet them; liquids that do not wet the tubes are depressed.* (*b*) *The elevation, or depression, is inversely proportional to the diameters of the tubes.* (*c*) *The amount of elevation or depression decreases as the temperature increases.*

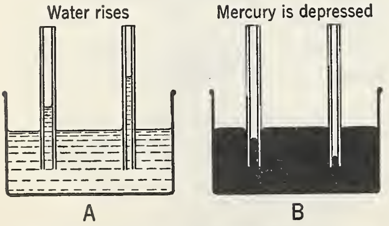


Fig. 138. *A*. Capillary action of water. *B*. Capillary action of mercury.

**120. We meet capillary phenomena in everyday life.** When one corner of a towel is held in water, other portions of the towel soon become wet. The spaces between the fibers are really small capillaries in which the liquid rises. The use of a towel in drying the hands is an application of capillarity. The absorption of ink by blotting paper, and the rise of oil in a lampwick, are further examples.

Capillarity may play an important part in the conservation of moisture in the soil. Rain water disappears in several ways: (*a*) Part of it runs off directly; (*b*) part evaporates; (*c*) some trickles through the soil and becomes a part of the subterranean drainage system; (*d*) some of it is absorbed or held by the soil, to be used by the roots of plants. The amount thus retained depends upon the kind of soil and *upon the size of its pores.* In very compact soil, the pores are small and capillary action brings the water to the surface, where it is lost by evaporation. Stirring the surface soil makes the pores larger and prevents a considerable portion of this loss. The so-called *dry farming* depends upon this principle. In Kansas, Nebraska, and other states where the rainfall is not much more than fifteen to twenty inches annually, good crops may be grown by making the subsoil compact to prevent subterranean loss, and keeping the surface stirred to prevent loss by capillarity.

**121. What is the nature of solution?** Everyone knows that a lump of sugar or a piece of salt put into a glass of water dissolves, or goes into solution. In these cases the water is the *solvent;*

the sugar or the salt, the *solute*. It is believed that a substance dissolves if the force of adhesion between its molecules and those of the solvent is greater than the cohesive force binding together its molecules. The molecules of the solute occupy the spaces between the molecules of the solvent. It is probable that molecular motion also plays an important part in the advancement of these molecules through the pores of the solvent.

Several interesting facts concerning solutions should be noted.

1. *A solution is of the same nature throughout;* each unit volume of the solvent contains the same amount of solute. A teaspoonful of sweetened coffee is just as sweet when taken from one part of the cup as from another.

2. *The solute does not separate from the solvent upon standing,* unless the temperature changes or some of the solvent is lost by evaporation.

3. *Only a definite amount of solute can be dissolved in a given amount of solvent at a certain temperature.* If the solvent holds all the solute it can at that temperature, it is said to be *saturated.*

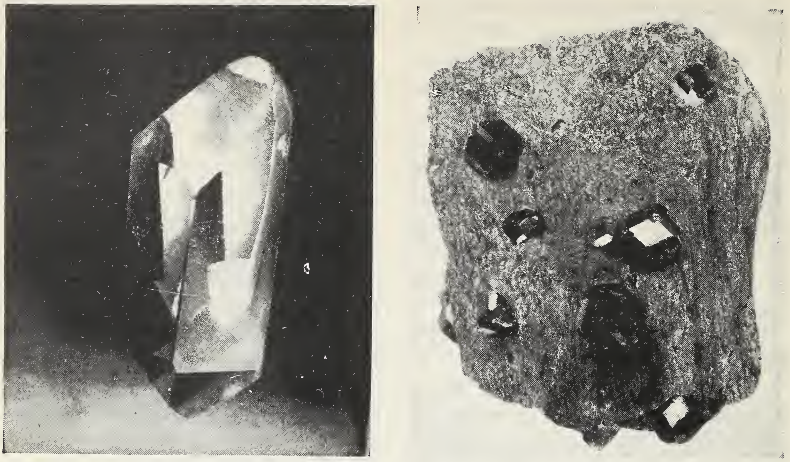
4. *The solubility of a solid generally increases with a rise of temperature.* Boiling water dissolves salt, sugar, etc., faster than cold water does, and it takes more of the solute to saturate the boiling water.

5. *The solubility of a solid varies with the nature of the solid and with the solvent used.* For example, salt dissolves readily in water, but glass is only slightly soluble. Rosin and shellac are almost insoluble in water, but they dissolve readily in alcohol. Grease is quite insoluble in water, but it dissolves readily in gasoline. On the other hand, many substances that are quite insoluble in alcohol or gasoline dissolve easily in water. Water is one of the best solvents known.

Both solids and liquids tend to lower the freezing point of a solvent when they are dissolved in it. During cold weather, men add alcohol or "Prestone" to the water in their automobile radiators to lower its freezing point.

**122. What is the nature of crystallization?** When the saturated solution of a solid is cooled or evaporated, some of the solid separates from the solvent in the form of crystals. Crystallization may also occur when a substance changes from the liquid to the solid state. During crystallization the molecules of the solid arrange themselves in regular geometric figures. The shape of the crystal depends upon the nature of the solid and the conditions under which crystallization occurs, Fig. 139. Granulated sugar, rock candy, and snowflakes are familiar examples of this beautiful phenomenon. The diamond differs from the graphite in your "lead" pencil only in the form in which the carbon particles of which it is composed have crystallized.

**123. How are liquids dissolved?** It is possible to dissolve one liquid in another. In such a case, either liquid may be considered the solvent. When two liquids are mutually soluble, they are said to be *miscible.* For example, alcohol and water will mix in all proportions. Oil and water are *immiscible.* When an oily liquid is vigorously shaken with water, finely divided particles of oil remain *temporarily* suspended in the water forming an *emulsion.* Milk is a good example of an emulsion, since the fat globules remain suspended in the milk for some time before the cream separates. In making mayonnaise dressing, egg yolks are added to make the emulsion of olive oil permanent.



*Courtesy of American Museum of Natural History, New York*

FIG. 139. Quartz crystal which shows incrusted phantom. Garnet crystals embedded in a rock. From Stickeen River, Alaska.

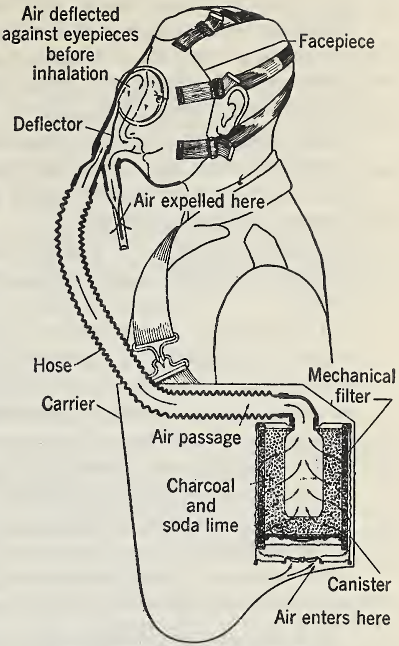
**124. How are gases adsorbed by solids?** Some porous solids, like charcoal, meerschaum, etc., have a great capacity for adsorbing gases. Freshly heated charcoal adsorbs 90 times its own volume of ammonia gas; it will adsorb 35 times its volume of carbon dioxide. The adsorption of gases by solids appears to be due to a condensation of the gas upon the surfaces of the solid; hence porous solids, having large surface areas, naturally have a great capacity for adsorption. Tailors put fuller's earth on a grease spot and then add gasoline. The gasoline dissolves the grease which is adsorbed by the fuller's earth as fast as it dissolves. Charcoal is a good deodorizing agent, since it readily adsorbs the gases that give rise to the odors. It was used very extensively in the World War for filling gas masks. It is very efficient in adsorbing poison gases, especially when it is impregnated with certain chemicals. Children in the United States collected coconut shells, pits, nuts, etc., to be used for making charcoal for gas masks. It was learned that charcoal made from these substances is about nine times as adsorptive as that made from ordinary soft woods. (See Fig. 140.) The gases that are given off by such foods as fish and onions are readily adsorbed by butter. For this reason butter kept in a refrigerator with onions soon acquires an "onion taste." A perforated can filled with charcoal may be used in a refrigerator to prevent the adsorption of gases by foods. Silica gel is useful too.

**125. How are gases absorbed by liquids?** Milk absorbs gases given off by foods quite as readily as does butter. If we heat a little water in a test tube, bubbles of gas soon begin to rise through the water. This gas may be shown to consist of air which was absorbed by the water. Water absorbs carbon dioxide even more readily than it does air, while ammonia gas is so readily absorbed that it is possible to dissolve nearly 1300 quarts of ammonia gas (S.T.P.) in one quart of ice water.

Heating a liquid decreases its capacity for absorbing gases. In other words, gases are *less soluble* in hot water than they are in cold water. For this reason ammonia gas is liberated when we heat household ammonia.

An increase of pressure increases the capacity of liquids for absorbing gases. In charging soda fountains, or in bottling carbonated beverages, carbon dioxide gas is forced into the liquid under a pressure of several atmospheres. When the pressure is released, part of the absorbed gas bubbles off and escapes at the surface of the liquid. The effect of pressure upon gas absorption was studied quantitatively by Henry. He found that *the amount of gas that can be absorbed, or dissolved, in a liquid is directly proportional to the pressure.* This statement is known as HENRY'S LAW. At a pressure of two atmospheres, one can dissolve twice the amount of carbon dioxide in water, for example, that he can when the pressure is only one atmosphere.

In many cases it seems probable that gases which are dissolved in water are held in solution physically. In other cases, the gas doubtless unites with the water to form a chemical compound which is soluble. There is no English term to distinguish between these two kinds of solution. It is not accurate to say that metals dissolve in acids.



Army gas mask showing passage of inspired and expired air

*Courtesy of the War Department*

FIG. 140. Official gas mask. Within a week after the Germans first released chlorine gas against the Canadians at Ypres, 2,000,000 simple gas masks had been distributed to French and British soldiers. They were made of veiling bags filled with "hypo" crystals. From such home-made masks the modern gas mask, suitable for use in World War II, has grown. It contains activated charcoal for adsorbing gases. The charcoal is impregnated with various chemicals which unite with the poison gases and form harmless compounds.

## Summary

All matter is made up of exceedingly small particles called molecules. These molecules are always in motion.

There are several evidences of the correctness of the kinetic theory of matter. For example, gases expand indefinitely; the movement of particles in a solution can be detected with the ultramicroscope; gases exert pressure upon the walls of their containers; gases diffuse rapidly; gases pass through membranes by osmosis.

The diffusion, evaporation, and osmosis of liquids are all evidences that their molecules are in motion. The diffusion and evaporation of solids furnish evidence of molecular motion.

Cohesion is the force of attraction between like molecules; adhesion is the force of attraction between unlike molecules.

When an object rebounds, the angle of rebound is equal to the angle of incidence, provided that the object is perfectly elastic.

Hooke found that elastic deformations are directly proportional to the distorting force, if the elastic limit be not exceeded. Or, strain is directly proportional to stress.

Liquids behave as if a thin elastic film were stretched over their surfaces. The film is contractile. It pulls free liquids into a spherical shape.

The elevation or depression of liquids in tubes of small diameter is known as capillarity. Liquids that wet the tubes are elevated by capillary action; those that do not wet the tubes are depressed; the amount in either case is inversely proportional to the diameter of the tube. The amount is also inversely proportional to the temperature.

The solubility of a solid usually increases as the temperature increases. Cooling a saturated solution, or evaporating some of the solvent, causes the separation of some of the solute in the form of crystals.

The solubility of gases decreases with an increase in temperature.

The amount of gas that can be dissolved in a liquid is directly proportional to the pressure, a statement known as Henry's law.

*How many of the following terms can you define or explain?* (*Make your own diagnosis.*)

Molecule
Kinetic
Brownian movement
Diffusion
Osmosis
Evaporation
Cohesion
Adhesion
Elasticity
Compression
Torsion
Stress
Strain
Flexion, flexure
Elastic constant
Elastic limit
Hooke's law
Safety factor
Surface tension
Viscosity
Meniscus
Capillarity
Solubility
Crystallization
Miscible
Emulsion
Absorption
Adsorption
Henry's law
Shape of free liquid

## QUESTIONS

1. Why is osmosis of gases and liquids so important?

2. Why does not the carbon dioxide of the air collect near the floor of a room?

3. Why does putting salt on a garden snail or slug cause it to become wrinkled?

4. If a non-corrosive liquid is to be introduced into the eye, why should it have the same density as the fluids inside the cell walls?

5. Explain the action of a towel in drying the hands.

6. Why is a paper that is to be used with ink covered with sizing?

7. When a glass rod is cut off, its edges are very sharp. Why do they become rounded when they are held in the flame until the glass is softened?

8. Shot are made by pouring molten lead on sieves supported at a considerable height, from which drops of molten lead fall into a vessel of water. Why are they rounded?

9. A blacksmith welds two pieces of

iron together by heating the ends, lapping them, and then pounding them on an anvil. Explain the principle involved.

10. Chemists hold a glass rod against the side of a beaker from which a liquid is being poured. What is its function?

11. Why is a pen to be used for writing with ink split at the point?

12. Is the air inside a soap bubble denser or rarer than the air outside? Explain.

13. Fish die in an aquarium unless the water is frequently renewed. Explain.

14. Why does effervescence occur when soda water is drawn from a soda fountain?

15. Water drawn from the hot water tap quite often appears milky. Explain.

16. What principle of physics does a dentist use when he taps successive layers of gold foil into the cavity of a tooth?

17. What precautions should be taken in storing foods in a refrigerator?

18. What is meant by the term "Brownian movement"?

19. What are some of the most striking proofs of the molecular motion of gases?

20. Why is blotting paper effective in taking up excess ink? Is the use of sand similar in principle?

## PROBLEMS

### Group A

1. A wire 1 mm. in diameter is stretched 0.1 mm. by a certain weight. How far will a wire 3 mm. in diameter be stretched by the same weight if it is of the same material and of equal length? (The strength of a wire varies as the square of the diameter.)

2. Two wires have the same diameter. One is 1 ft. long, and the other is 10 ft. long. If it takes a force of 10 lb. to break the first wire, what force will be needed to break the second one?

3. If you were given a coiled spring, a metal frame, a ruler, one weight of 1 gm., and another of 10 gm., how would you proceed to make a spring balance that would weigh up to 250 gm.?

4. Upon a spring balance, the ounce marks are 1 mm. apart. How long a scale will be needed if the balance is to be used for weighing 10 lb.?

5. One liter of ice-cold water absorbs 1.7 gm. of carbon dioxide when it is under a pressure of 1 atmosphere. How many gm. of carbon dioxide can be absorbed under a pressure of 6 atmospheres?

### Group B

6. A wire 1 mm. in diameter can support a weight of 25 lb. What must be the diameter of a wire of the same material that must support a weight of 100 lb.? (The strength of a wire varies as the square of the diameter.)

7. The cross-sectional area of a wire is 0.0002 sq. in. It takes a force of 40 lb. to break this wire. What is its tensile strength?

8. The tensile strength of a bronze wire is 120,000 lb. per sq. in. If it takes a force of 50 lb. to break a piece of such wire, what is its diameter?

9. It takes 50 lb. to break 1 ft. of a given wire. How many lb. will be needed to break a wire of double the length, double the diameter, and double the tensile strength?

10. A piano wire, sp. wt. of 7.8, is suspended at one end. If its tensile strength is 375,000 lb. per sq. in., how long must the wire be to break of its own weight?

11. What force is needed to break the wire of No. 10, diameter 0.03 in.?

# Unit Three

# *Force and Motion*

## Preview

IN THE STUDY OF THESE TOPICS, TWO GREAT NAMES STAND out conspicuously. One of them, Galileo Galilei, was born in the sixteenth century and did most of his work in the early seventeenth century. The year that Galileo died, Sir Isaac Newton was born. We see Galileo building a telescope, studying the acceleration of a ball rolling down an inclined plane, dropping various objects from the top of the leaning tower at Pisa, working out the facts pertaining to the vibrations of a pendulum, and agreeing with Copernicus that the sun and not the earth is the center of the solar system. He was in advance of his time, and he was at one time forced to retract some of his scientific statements, because the leaders of his church considered some of his teachings heretical. Sir Isaac Newton is doubtless best known for his formulation of the law of gravitation. He was a great mathematician, too. His views on light and other scientific subjects were accepted to a large degree for a century or more. Then, too, we have Newton's laws of motion, which tell us how a moving body behaves.

Force and motion are closely related. Force may be great enough to produce motion. A moving body, too, is capable of exerting force upon an object with which it collides. We also use force to stop motion.

In this unit we shall study the force of gravitation and other such natural forces as wind and running water, in addition to the forces which man can exert, either acting by himself or with others, or by the use of machines. This unit deals with both uniform motion and accelerated motion. It is just as important to know how to stop a moving car as it is to know how quickly one can accelerate. In stopping a car, one needs to use uniformly decelerated motion.

# Force

## 1. Gravitation and Weight

**126. What is force?** The term "force" is not entirely new to us, but perhaps we need to discuss it more fully. It has been defined as a "push" or a "pull"; it may also be defined as muscular exertion or its equivalent. If we pull upon a locomotive, we may move it or we may merely *tend* to move it. In either case we are using force. A truck starts down hill; if we push backward against it we may stop it, or we may merely *tend* to stop it. We are using force in either case. Some forces are tiny ones, while others are stupendous. *Forces produce or prevent motion, or they have a tendency to do so.* Man sometimes uses the force of the wind, the waves, and the tides for his own purposes. Sometimes he uses other forces to try to counteract the destructive forces of these agents. (See Fig. 141)

**127. What is the force of gravitation?** Before a child learns to walk, he frequently experiences the force of gravitation. He finds that bodies fall toward the earth. He cannot tell why, and neither can anyone else. We say that bodies fall toward the earth because they are attracted by *gravity*, or that most common of all forces, *gravitation.*

FIG. 141. When the velocity of the wind in a tornado reaches from 100 to 200 miles per hour, it destroys practically everything in its path.

---

### Vocabulary

RESULTANT, a single force that can be substituted for two or more forces without altering the effect.

EQUILIBRANT, a single force that prevents motion.

CENTER OF GRAVITY, that point in a body at which all its weight seems to be concentrated.

COUNTERPOISE, a weight used to counterbalance another.

GRAVITATION, the force of attraction between two bodies.

Sir Isaac Newton called attention to the fact that gravitation is *universal,* and also that the attraction between bodies is *mutual.* The force is *universal* because it applies to the earth, the sun, the stars, and all bodies in the universe. It is *mutual,* because an apple attracts the earth, as well as being attracted by the earth. The earth attracts the moon, and the moon also attracts the earth. (See Fig. 142.)

The magnitude of the force of mutual attraction depends upon two things: (*a*) The masses of the bodies; (*b*) the distance between their centers. It takes twice the force to lift two bricks that it does to lift one, because we must overcome the earth's attraction for twice as much mass. The song "Distance lends enchantment" does not apply to the mutual force of gravitation, because the force of attraction between two bodies decreases as the square of the distance between their centers increases. Newton did not discover gravitation, but he formulated the following law: *Every body in the universe attracts every other body with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.* An object at the surface of the earth is about 4000 miles from its center. If it were taken up to a height of 1000 miles, it would then be 5000 miles from the earth's center. The earth's attraction for it would then be only 16/25 as much as before. $(4000)^2 \div (5000)^2 = 16/25$. A body that weighs 100 lb. at the earth's surface will weigh only 64 lb. at a height of 1000 miles above the surface. (See Fig. 143.)

*Wide World. Philadelphia Bureau*

FIG. 143. A heavy modern United States Army tank. It is being piloted over a dummy jeep in a public demonstration. This is a sixty-ton tank. Some of our tanks in use in World War II weigh as much as eighty tons.

*Science Service*

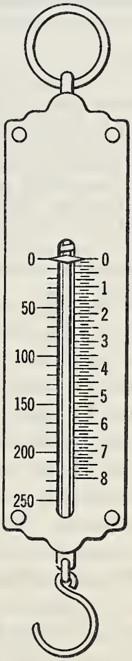
FIG. 142. Sir Isaac Newton (1642–1727) was a famous philosopher and a mathematical genius. He stated the law of gravitation and the laws of motion. He discovered that white light is composed of seven colors, and he explained the color fringe of films. In mathematics he laid the foundation for the calculus.

**128. What is weight?** We have already defined the weight of a body as the measure of the earth's attraction for that body. When we say that a man weighs 200 lb., we mean that he attracts the earth with a pull of 200 lb., and that the earth's attraction for him is equal to 200 lb. Since all parts of the earth's surface are not equidistant from its center, we would expect the weight of an object to vary in different localities. For example, a body will weigh slightly less on top of a mountain than it does in a valley. Since the earth is slightly flattened at the poles, a man will weigh slightly more at the North Pole than he does at the equator. A man who weighs 189 lb. at the equator weighs about 190 lb. at either pole.

If a hole were bored down into the earth and a body were lowered into it, its weight would not keep increasing as it descended beneath the surface. It is true that it would be getting nearer the earth's center, but the gravitational pull of the material above it would cause it to weigh less when it was *beneath* the surface. A body will have its greatest weight *on that part of the surface* which is nearest the earth's center, but it will lose in weight if carried above the surface or lowered beneath it.

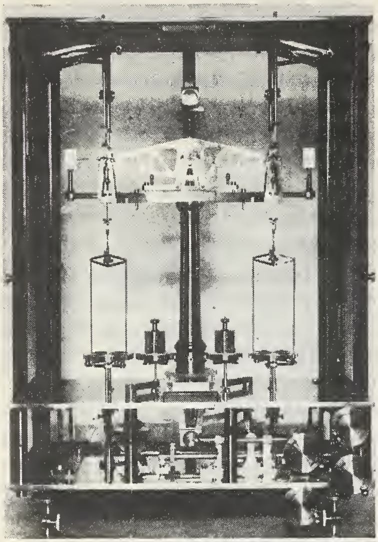
The mass of the sun is so much greater than the mass of the earth that an object which weighs 100 lb. on the earth would weigh at the surface of the sun about 2700 lb. The force of gravitation on the moon is so much smaller than it is on the earth that a person on the moon would weigh only about one-sixth as much as he does on the earth. An athlete on the moon could easily jump from 25 to 30 ft. high, but on the sun he would be unable to lift his foot.

**129. How is force measured?** The spring balance is one of the most common ways to measure force. It is an application of Hooke's law. The pull of the earth upon *one gram of mass* suspended from the hook of the balance will stretch the spring a certain distance. Two grams of mass will stretch the spring twice as far, and so on. The graduations are marked upon the face of the balance, which is independent of the spring. A pointer attached to the spring indicates the reading. (See Fig. 144.) In the use of the beam balance for measuring forces, the pull of the earth upon the object placed upon one beam of the balance is counterpoised by weights of known magnitude placed upon the other beam. Some balances



27
120
540
27
3240

Fig. 144. The spring balance may be used to measure force.



*Courtesy of Dayton C. Miller, Case School of Applied Science*

Fig. 145. The Rueprecht balance was constructed especially for the Case School of Applied Science. Under a load of 1000 gm., this balance is sensitive to 0.000,002 gm. The balance may be counterpoised when two one-lb. weights are placed side by side on one side of the balance. If one of the weights is then placed on top of the other, thus removing it slightly farther from the center of gravity of the earth, the balance is sensitive enough to show a reduction in weight.

of this type are exceedingly sensitive. (See Fig. 145.) In assaying gold ores it is necessary to use very sensitive balances. In the chemical laboratory, micro-balances are used to weigh minute quantities of material. Much attention is given to micro-analysis, in which the chemist must determine the amount of poison or other chemical, even when present only in tiny grains or crystals.

**130. What are the units of force?** To measure forces, or to compare them, some definite units must be used. In all our work, we have used the *gram of force* and the *pound of force*. They are called the *gravitational units*, since they are based upon the earth's attraction. For example, a gram of force is the pull which the earth exerts upon one gram of mass, and the pound of force is the pull which the earth exerts upon one pound of mass. But the earth's pull upon one gram of mass is greater at the poles than it is at the equator; it is more in a valley than upon a mountain top. For the same reason that weight, or the measure of the earth's attraction, varies, these units also vary. At the latitude of New York, *a gram of force acting continuously for one second upon a gram of mass imparts to it a velocity of approximately 980 cm. per second.* At the equator this velocity is only about 978 cm. per second, but at the North Pole it is about 983 cm. per second. *A pound of force acting for one second upon a mass of one pound imparts to it a velocity of 32.16 ft. per second.*

★The student of elementary physics nearly always uses the gravitational units, but engineers must have units of measurement that are independent of the varying force of gravity. The *absolute units* of force are based upon mass and not upon weight. They are also useful in defining other units used in heat and electricity.

In the metric system the *dyne* is the *absolute* unit of force. *One dyne acting for one second upon one gram of mass imparts to it a velocity of one cm. per second.* Therefore, the dyne is approximately equal to $\frac{1}{980}$ of a gram of force; or, 980 dynes equal one gram of force at the latitude of New York. In the English system the *poundal* is used as the *absolute* unit of force. *One poundal acting for one second upon one pound of mass imparts to it a velocity of one foot per second.* At New York, one pound of force equals 32.16 poundals.

## 2. Composition of Forces

**131. How do we represent forces?** Since a force has both magnitude and direction, we may use a straight line to represent a force. The point at which the force is applied must also be considered. Suppose, for example, that we wish to represent a force of 10 lb. acting in an easterly direction upon the point *P*. We may use a straight line ten units long, drawn in an easterly direction from the point *P*. (See Fig. 146.) Any *convenient* unit may be selected, but it is necessary to use the same unit if several forces are represented on the same diagram. We may let $\frac{1}{4}$ in. represent 1 lb., or 1 mm. represent 1 lb., or any other scale we wish. The choice of the unit will depend upon the amount of space available for the diagram.

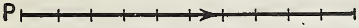


FIG. 146. A line is used to represent a force.

In Fig. 147, we have two forces represented; one force of 15 gm. acts in a westerly direction upon the point *P;* the other, a force of 20 gm., acts in a southerly direction upon the same point.

**132. What is a resultant?** Quite often two or more forces act simultaneously upon the same point. Sometimes it is desirable to find the point of application, magnitude, and direction of a *single* force that could produce the same effect as all the forces acting conjointly. *The resultant of two or more forces is that single force which could produce the same effect as the two or more forces acting together.*

The resultant of two or more forces is really a *substitute* for those forces. When the football coach sends a substitute into the game, he removes one player from the field. If we use the resultant or substitute force, we assume that it takes the place of two or more forces. After we have found their resultant, the separate forces need no longer be considered. Unlike the football substitute, who does not always produce the same effect as the man displaced, the resultant force must produce *exactly the same effect* as *all* the forces for which it is substituted.

**133. What is the resultant of forces acting in a straight line?** If we have one boy pulling on a rope with a force of 40 lb., and another boy joins him and pulls in the same direction with a force of 60 lb., the resultant in this case is equal to the *sum of the two forces.* If the boys stopped pulling, one man taking their place could produce the same effect by pulling in the same direction with a force of 100 lb.

If one boy pulls in one direction with a force of 40 lb., and another boy pulls in the opposite direction with a force

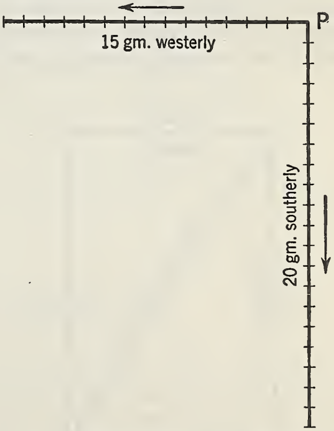


FIG. 147. Representation of two forces acting at an angle

of 60 lb., then the resultant is the *difference between the two forces.* In this case a force of 20 lb. pulling in the direction of the *greater* force would produce the same effect.

**134. How do we calculate the resultant of forces acting at right angles?** Suppose that one force of 10 gm. acts in an easterly direction upon an object at point *A*, Fig. 148, and another force of 15 gm. acts in a southerly direction upon the same point. Let us first plot the two forces. It is obvious that the first force acting alone tends to move the object along *AB* to *B*. The second force acting alone tends to move the object along *AC* to *C*. If the two forces acted *successively* upon the object it would arrive at point *D;* if they act *simultaneously,* it would also arrive at point *D*, but its line of motion would be along the diagonal of the parallelogram of which the two forces are sides. *The resultant of two forces acting at an angle upon a given point is equal to the diagonal of a parallelogram of which the two forces are sides.* Students of geometry know that the sum of the squares of the two sides of a right triangle equals the square of the hypotenuse. If we extract the square root of the sum of the squares of the two sides of the parallelogram, we can calculate the resultant. In the above example, $\sqrt{(10)^2 + (15)^2} = 18 +$ gm.

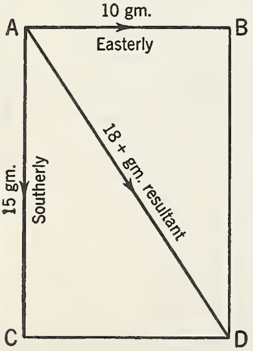


FIG. 148. Parallelogram of forces.

**★135. How do we calculate the resultant of forces acting at any angle?** It more often happens that the angle between two forces acting upon the same point is not a right angle. In Fig. 149, we have represented forces of 10 gm. and 15 gm. respectively, acting upon the point *A*. In this case the angle between the two forces is only 50°. Unless the student knows trigonometry, he cannot *calculate* the resultant of these two forces acting at this angle. To find the approximate value of the resultant, we draw a parallelogram, using the two forces *AB* and *AC* as sides. We must make the angle between them 50°. From the point *A* we draw a diagonal and measure it carefully. From the length of the diagonal, we find the equivalent of the resultant force in grams.

We find that the resultant is decidedly different if we use the same two forces, but make the angle between them 140°. The parallelogram is constructed in the same manner, using the forces as sides, and making the angle between them 140°. (See Fig. 150.) Of course the diagonal must be drawn from *A*. The resultant could never produce the same effect as the two

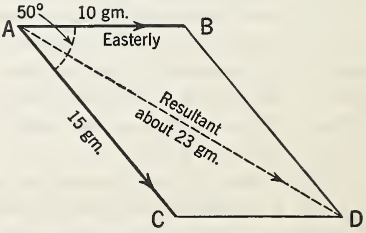


FIG. 149. Resultant of two forces acting at an acute angle.

forces acting at *A* if it were applied at *B*. Beginners sometimes make the mistake of drawing the wrong diagonal as the resultant. The diagonal is measured and its value determined as before.

Sometimes three or more forces act at different angles upon the same point. It is possible to find their resultant by finding first the resultant of two of them, using them as sides of a parallelogram, and finding the diagonal. Then we can construct another parallelogram, using as sides the third force and the diagonal of the first parallelogram. The diagonal of the second parallelogram is the resultant of the three concurrent forces.

**136. What is the equilibrant?** Sometimes it is desirable to find the point of application, magnitude, and direction of a force which could be applied to produce *equilibrium*, or *to prevent motion.* A boy pulls on a wagon with a force of 40 lb. A second boy pulls on the wagon with a force of 40 lb. in exactly the opposite direction. He prevents motion, or produces equilibrium. The force he uses is called the *equilibrant.*

It is quite as easy to find the equilibrant of two or more forces acting upon a point. We must first find their resultant and then apply the equilibrant in an opposite direction. In Fig. 148 we found that a single force, 18 + gm., can be substituted for the two forces *AB* and *AC*. By removing the two forces, and leaving their resultant *AD*, we find that the equilibrant force represented by *AE must be applied at the same point A, its direction must be directly opposite to that of the resultant, and its magnitude must be equal to the magnitude of the resultant.* (See Fig 151.) Hence we conclude that *the equilibrant of two or more forces is always equal and opposite to their resultant.*

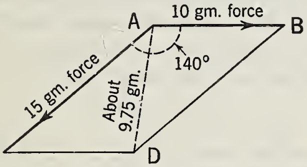


Fig. 150. Resultant of two forces acting at an obtuse angle.

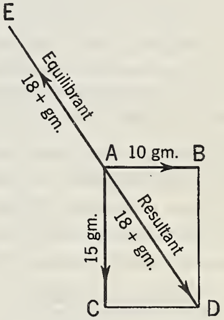


Fig. 151. The equilibrant prevents motion.

## 3. Resolution of Forces

**137. What is the resolution of forces?** We have just learned how to find a single force that could produce the same effect as two *component* forces. When the forces acted at an angle, our problem became one of a simple construction in geometry: given the two sides and the included angle of a parallelogram, to construct the parallelogram and draw its diagonal.

Now if we have given the resultant of two forces acting at an angle, one of the forces, and the angle included between that force and the resultant, we should be able to find the value of the other force. Our problem in this example of *resolution* of forces is the converse of that in *composition* of forces. We have given the diagonal of a parallelogram, one of the sides, and the angle between that side and the diagonal. The problem is to construct the parallelogram and find the other side.

PROBLEM. Two forces act upon the point *A;* one force of 8 gm. acts in a southerly direction; an unknown force acting at an angle with the 8-gm. force produces the same effect as a single force of 10 gm., acting in a direction 37° East of South. Find the magnitude and direction of the unknown force.

*Solution.* Construct a parallelogram, using for one side the 8-gm. force, $AB$, acting southerly. (See Fig. 152.) Using a protractor, measure off an angle of 37°, East of South, and draw a line $AC$ to represent the resultant force, 10 gm. Use this resultant force as the diagonal of a parallelogram and construct the parallelogram. The side $AD$ of the parallelogram is the unknown force.

**★138. How is the force of gravity resolved?** *Inclined Plane.* It quite often happens that a force acts upon an object in a direction in which the object is not free to move. Such a force may be resolved into two components. An object resting upon an inclined plane is acted upon by gravity with a force equal to its weight. (See Fig. 153.) The plane prevents the motion of the object in the direction $OW$, but this resultant force $OW$ may be resolved into two components. One component, $OD$, acts perpendicular to the surface of the plane, and tends to break the plane. The other force, $OR$, acts parallel to the plane, tending to pull the object down the plane.

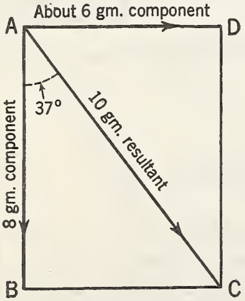


FIG. 152. The horizontal component of the force is 6 gm.

Upon the diagonal $OW$, we may construct the parallelogram $ORWD$, and find the *relative* values of the sides $OR$ and $OD$ by plotting to scale. In this especial case, we can calculate these values if the height and length of the plane are known. The triangles $ABC$ and $WOR$ are similar. (The sides are mutually parallel and perpendicular.) Hence, $OR : OW = BC : AB$. But $OR$ represents the force or effort, $E$, tending to pull the object down the plane; $OW$, the weight or resistance, $R$, of the object; $BC$, the height of the plane; and $AB$, the length of the plane. Hence, the effort bears the same relation to the *resistance* that the height of the plane does to its length. Or,

$$E : R = h : l.$$

In the same manner it may be shown that the force tending to break the plane bears the same ratio to its weight that the base of the plane does to its length.

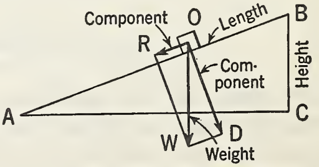


FIG. 153. Resolving a vertical force into its components.

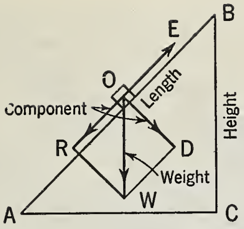


Fig. 154. Component parallel to plane increases as we make the plane steeper.

Making the plane steeper increases the force *OR* in proportion to the weight and decreases the force *OD*. (See Fig. 154.) The force *OE*, which is equal and opposite to *OR*, represents the effort needed to keep the object from sliding down the plane. The steeper the plane, the greater this force becomes.

★**139. There are other applications of resolution of forces.** When one pushes a lawn mower, he wishes the mower to move along the surface of the ground, but he pushes at an angle to the ground because it is more convenient. The force that he applies, Fig. 155, is resolved into two components. One component pushes the mower forward parallel with the lawn; the other acts perpendicularly and it tends to push the mower into the ground. Suppose that one pushes with a force of 80 lb. at the angle shown in the figure. By constructing a parallelogram to scale, we find that the horizontal component is about 74 lb.; the vertical component, which tends to push the mower into the ground, is approximately 31 lb.

When a boy pulls a loaded sled, the force which he exerts is resolved into two components. The horizontal component draws the sled forward; the vertical component tends to lift the sled vertically.

When a sailboat is moving with the wind, the full force of the wind drives the boat forward. When the boat is moving at an angle with the direction of the wind, part of the force of the wind drives the boat forward, and the other component *tips* the boat. (See Fig. 156.)

In the case of the guy wire on a telephone pole, one component tends to pull the pole into the ground, and the other acts horizontally. When a switch engine on one track pushes a freight car on a parallel track, the thrust force is resolved into two components. One component moves the car along the track, while the other component tends to spread the rails apart. (See Fig. 157.) In the builder's crane or in the steam shovel, the boom must be stiff enough to resist by a thrust force the combined effect of the weight on the rope or chain

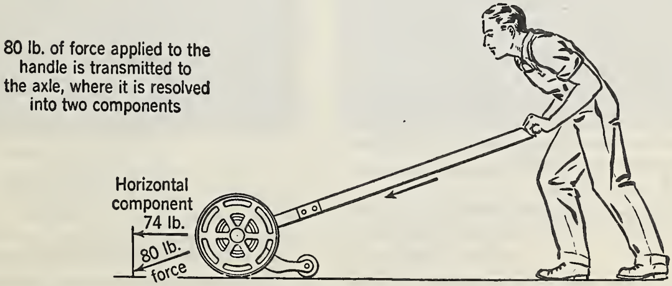

80 lb. of force applied to the handle is transmitted to the axle, where it is resolved into two components
Horizontal component 74 lb.
80 lb. force

Fig. 155. The force applied to the handle of the mower is resolved into two components

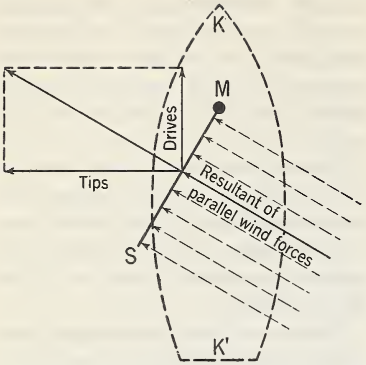

K
M
Drives
Tips
Resultant of parallel wind forces
S
K'

FIG. 156. The wind acts against the sails and is resolved into two components.

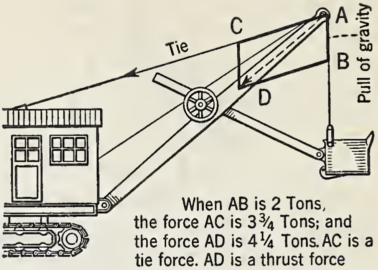

A
C
Tie
B
D
Pull of gravity
When AB is 2 Tons,
the force AC is 3¾ Tons; and
the force AD is 4¼ Tons. AC is a
tie force. AD is a thrust force

FIG. 158. How forces are resolved in a steam shovel.

and the tie force. If the thrust force and the weight are known, the value of the tie force may be found. (See Fig. 158.) In a house or barn, the weight of the roof acts downward and outward upon the walls of the house. By reference to Fig. 159, we can see how the weight of the roof is resolved into the two components. To support a weight *OW* applied at *O*, the combined upward thrusts *OM* and *OS* of the rafters must produce a resultant force equal to *OR*.

**140. The airplane is invented.** For centuries men have dreamed of flying. Within the memory of the present generation those dreams have come true. At first men tried the use of gliders. But in December, 1903, Orville Wright made the first flight in a power-driven airplane at Kitty Hawk, North Carolina. (See Fig. 160.) Since that time, great progress has been made in the science of aviation. Man has made altitude flights of about $10\frac{1}{2}$ miles. Domestic airlines now fly, yearly, over one and a half billion passenger miles safely at rates of from 180 to 230 miles per hour. Military planes have attained speeds of over 400 mi. per hr. Some can carry a load of well over 16,000 lb. To range forests and protect them against fires, and to spray cotton fields with poison to kill the boll weevil, airplanes are also much used. (See Figs. 161 and 162.) Commercial aviation is only in its infancy.

New materials have been developed, and also new processes of construction,

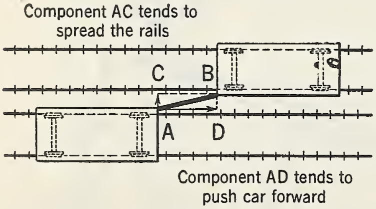

Component AC tends to spread the rails
C
B
A
D
Component AD tends to push car forward

FIG. 157. The force *AB* is resolved into two components.

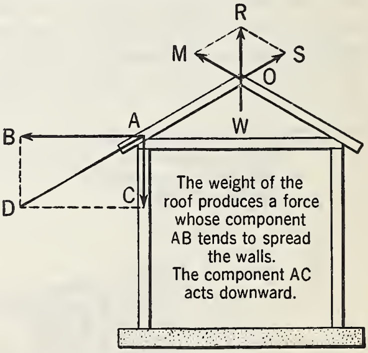
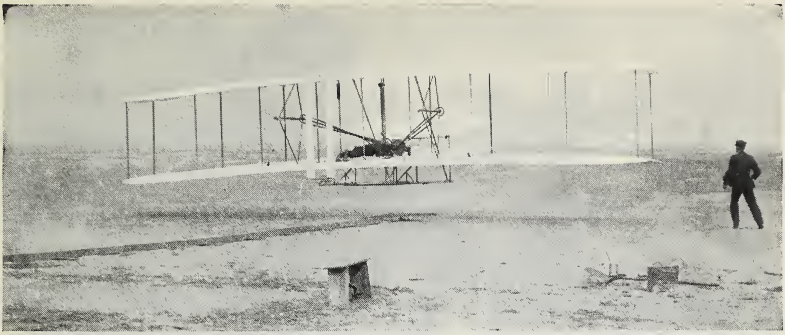

R
M
S
O
A
W
B
C
D
The weight of the roof produces a force whose component AB tends to spread the walls.
The component AC acts downward.

FIG. 159. The weight of the roof pushes downward and also tends to spread the walls.



Courtesy of Orville Wright

FIG. 160. The Wright brothers began their experiments in aëronautics by the use of gliders. Thus they gained experience and skill in manipulation. By placing a rudder in the front part of the plane, they were the better able to study wind effects. Then they were ready for the attachment of the gasoline motor. The first flight with a power-driven airplane was made at Kitty Hawk, North Carolina, December 17, 1903. Orville Wright was in the plane and his brother Wilbur, on the ground. Of four flights made that morning, the longest was 59 sec. and the distance 852 ft. After five years of further experimentation, they submitted to the Signal Corps of the United States Army a biplane with two propellers, driven by a 25-horsepower engine. One flight lasted one and one-quarter hours at an estimated speed of 40 miles per hour.

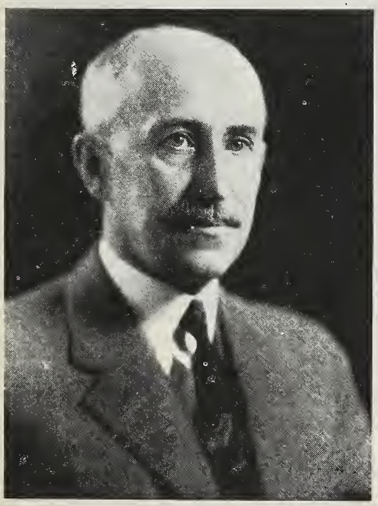
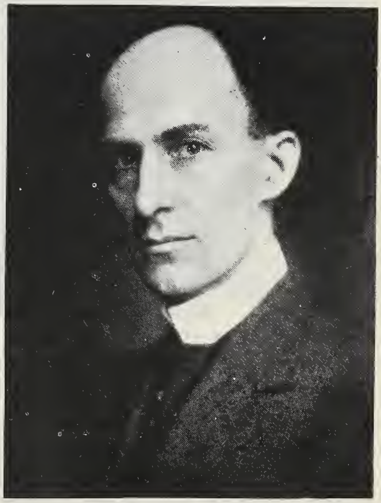
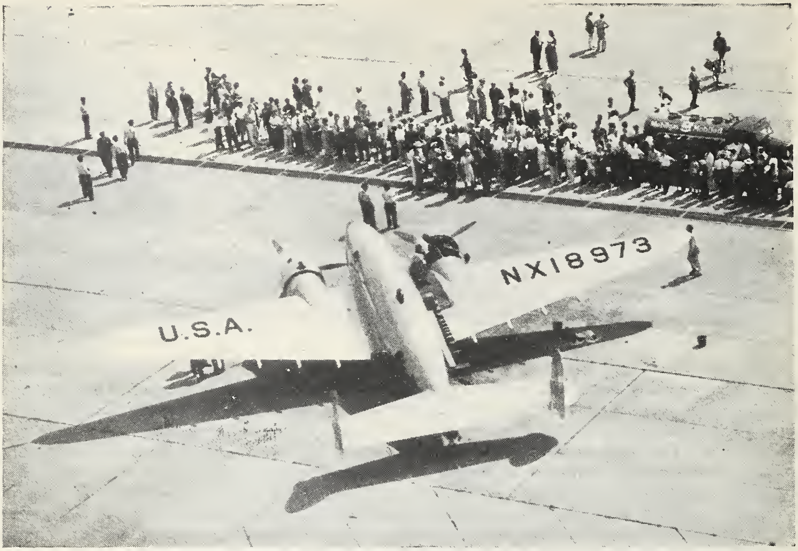


FIG. 161. Orville Wright (1871– ) worked with his brother Wilbur to bring to successful completion the invention of the power-driven airplane. The Wright brothers are the sons of Bishop Milton Wright, D.D.



Courtesy of Orville Wright

FIG. 162. Wilbur Wright (1867–1912) was one of the inventors of the modern power-driven airplane. The work was begun in the bicycle shop of the Wright brothers at Dayton, Ohio.



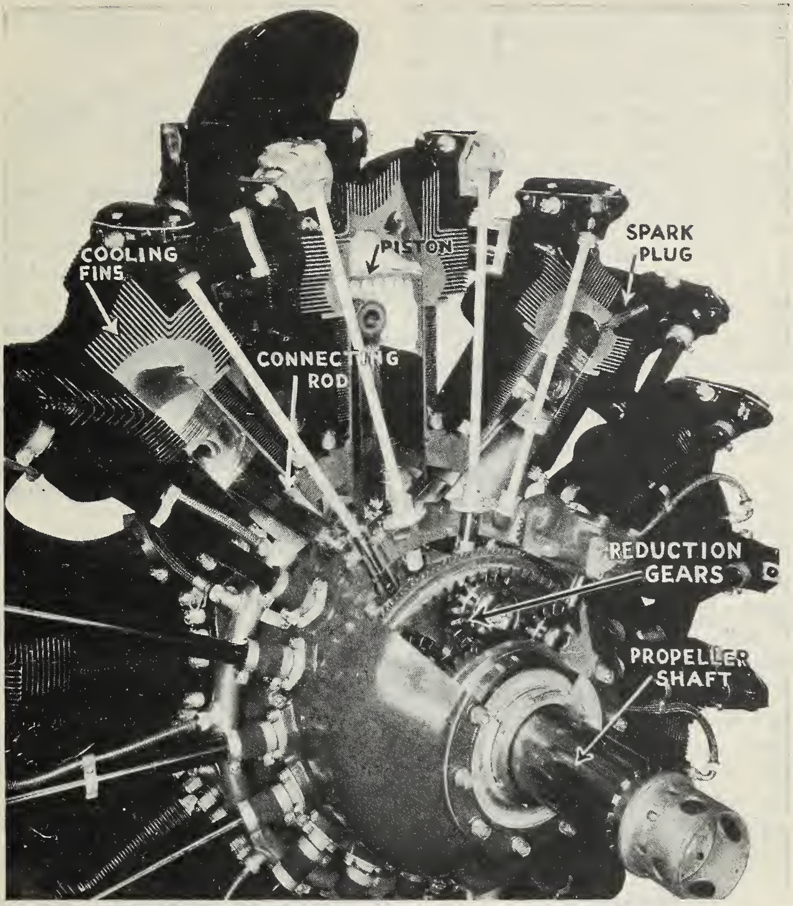
New York Daily News

FIG. 163. The airplane in which Howard Hughes made his famous round-the-world flight.

until the airplane is now made largely of metal. Curved bakelite seems to be a satisfactory material for use in airplane construction. The flights of Colonel Charles Lindbergh across the Atlantic Ocean and those of Rear Admiral R. E. Byrd over the poles of the earth furnish convincing proof that the modern airplane is rugged and trustworthy. The *China Clipper* makes regular flights across the Pacific Ocean, from island to island. Howard Hughes, starting July 10, 1938, on a flight around the world, flew from New York to Paris in 16 hours, half the time it took Lindbergh to make the flight. He flew at an average speed of over 200 miles per hour in his 13,000-mile flight across the Atlantic, over Russia, Siberia, and back across Canada. (See Fig. 163.)

Airplanes are driven by light, high-powered gasoline engines. Some of these engines develop more than one horsepower for every pound of their weight. Figure 164 shows a Wright whirlwind motor of the type used in the *Spirit of St. Louis*. Since airplanes are heavier than air, they cannot rise vertically. Hence they must be fitted with wheels to permit them to run along the ground until they acquire sufficient speed to enable them to rise. *Hydroplanes*, or *seaplanes*, are fitted with boat-shaped pontoons designed to enable them to "take off" from the water, or to alight upon it.

**★141. How is an airplane supported?** Since airplanes are heavier than air, they must be partially supported by the *upward* component of some force. The wing, or airfoil, has its front edge slightly higher than the rear edge. (See Fig. 165.) In normal flight, the angle amounts to only a few degrees, varying from 3 to 6. As the plane is



*Courtesy of the Wright Aeronautical Corporation*

FIG. 164. Wright Cyclone engine.

pulled or pushed forward by the thrust force of the propeller, a relative wind is produced. This has the same effect as that of a wind blowing against the airplane. In Fig. 165 the arrows show the direction of the relative wind. Thus the air exerts a pressure, *CS*, acting nearly at right angles to the plane. This air force is resolved into two components, one acting vertically, and represented by *CF;* the other component, *CD*, opposes the action of the propeller. This upward component is called *lift*, and the other component *drag*. To keep the airplane in steady flight, the *lift* force must equal the weight of the plane, and the *drag* force must balance the thrust force.

There is another factor which plays

an important part in supporting an airplane. As the plane moves forward, the air slides along the surfaces of the plane. But it moves much more rapidly over the upper surface of the plane; the angle made by the relative wind against the under surface somewhat retards the movement of the air. Just as the wind blowing across the top of a chimney drags air molecules along with it and reduces the pressure of the air in the chimney, so the rapidly moving air reduces the air pressure *above* the plane. Since the air pressure against the lower surface of the plane is greater than that above, the difference in these pressures helps support the plane. This is really an application of a principle stated by Bernouilli. *The high velocity of the fluid moving past the upper surface produces low pressure against that surface.* (See Fig. 166.) (Refer to Part 2, Chapter 29.)

★**142. Other applications of the Bernouilli effect.** *a. Baseball curves.* A baseball which is not spinning may travel in a straight line. But any boy knows that a spinning ball will move along a curved path. If we refer to Fig. 167, we find that the explanation is quite simple. The ball, spinning in a counterclockwise direction, drags the adjacent air around with it, as represented by the dotted circles. At the top of the ball this air is *moving with* the air current set up by the forward motion of the ball, and at the bottom it is *moving against* these currents. The air at the top moves faster and the pressure there is reduced. Thus the ball will move along the path shown by the dotted curve.

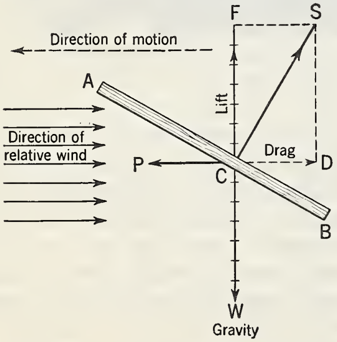


Fig. 165. The air force is resolved into one upward and one horizontal component.

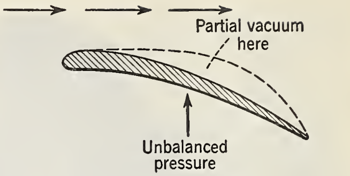


Fig. 166. The unbalanced pressure helps to support the airfoil, or plane.

When a tennis player hits the ball a glancing blow, he imparts to it a spinning motion. Then it travels along a curved path, and it takes a peculiar bound. A "sliced" or "hooked" golf ball is also an application of Bernouilli's principle.

*b. The Venturi meter.* A meter which may be used to measure the flow of water depends upon Bernouilli's principle. When water flows through the tube of Fig. 168, its velocity is increased as it flows through the constricted portion of the tube. From the pressure tubes, one can see that the pressure decreases as the velocity of the water increases. It is possible to

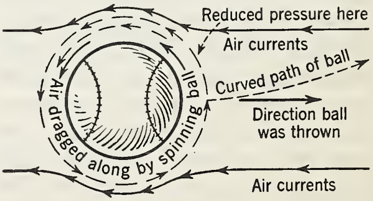


Fig. 167. The curving baseball is an application of the Bernouilli Principle.

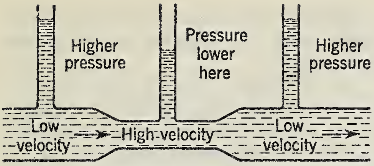


FIG. 168. As the water flows more rapidly through the constriction in the tube, the pressure is lowered.

calculate, from the difference in pressure in the vertical tubes, the velocity of the water in the horizontal tube. Such tubes can be used to measure the velocity of gases, too. The Venturi tube finds use in the carburetor of a gas engine. The tube around the gas jet is constricted to increase air velocity and accelerate evaporation.

## QUESTIONS

1. If a hole were bored through the earth and a ball dropped into it, where do you think it would come to rest? Explain.

2. A professor at Oxford University went before his class, threw a ball into the air, and remarked: "Behold, gentlemen! I throw a ball into the air; the earth rises to meet it, and the stars in heaven bow down to greet it." Explain what he meant.

3. Would a gram of force at the sun be greater than a gram of force at the earth's surface?

4. Is a dyne of force greater at the sun's surface than it is at the surface of the earth? Give a reason for your answer.

5. Why would you lower the handle of a lawn mower in pushing it through tall grass? Use a diagram to clarify your explanation. Does your diagram seem to indicate that a boy works to better advantage than a man when mowing the lawn?

6. Does a man weigh more at the North Pole or at the equator? Does he weigh more on top of a mountain or at its base?

7. A spring balance is graduated to read pounds at New York. If this balance were used to weigh meat at the North Pole, would you get more meat or less in a 5-lb. roast? Suppose a platform balance were used, would you get more meat at New York or at the North Pole?

8. A hammock is 8 ft. long. Is it more likely to break if the ends are attached to posts 5 ft. apart or 7 ft. apart? Use a diagram in your explanation.

9. Is it easier to pull yourself up if you grasp the bar of a trapeze with your hands 1 ft. apart or when they are 2 ft. apart? Explain. Try the experiment.

10. Why is it easier to throw a curved ball than a straight one?

11. Cut a sheet of paper about 2 in. square. Stick a pin through the center of the paper and place it on one end of a spool, as shown in Fig. 169. Why is it impossible for you to blow the paper away by blowing through the spool?

12. Before one can represent a force graphically, what three things must be known? How do you determine what scale you should use?

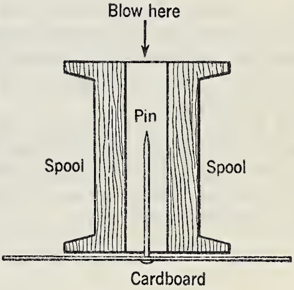


FIG. 169. Bernouilli effect.

## PROBLEMS

### GROUP A

1. One force of 40 gm. acts in a westerly direction upon a given point, and a second force of 35 gm. acts northerly. Represent graphically, and calculate the resultant.

2. By means of a graph, find the resultant of two forces acting upon the same point, if one force of 28 lb. acts southerly, and the other force of 40 lb. acts westerly. Calculate the resultant of the two forces. How do the two answers compare? Which

method do you think is more accurate?

3. Given two forces, 12 and 15 lb. each, acting upon the point P. Find their resultant: (*a*) when the angle between them is 180°; (*b*) when the included angle is 120°; (*c*) when it is 90°; (*d*) when it is 60°; (*e*) when it is zero.

4. A force of 30 lb. acts easterly upon the point *P*. A second force of 50 lb. acts southwesterly. Represent graphically and show the length and direction of the equilibrant. What is the value of the resultant?

5. Find the resultant of two 50-lb. forces, when the included angle between them is 60°.

6. An inclined plane is 12 ft. long and one end is 4 ft. higher than the other. A weight of 300 lb. rests on the plane. Find the value of the force tending to break the plane, and of the force needed to keep the weight from sliding down the plane.

7. Find the equilibrant of two forces of 200 lb. each, if the angle included between the two forces is 45°.

### Group B

8. Find the resultant of 3 forces acting upon the same point. One of 20 lb. acts northerly, one of 25 lb. acts easterly, and one of 30 lb. acts southeasterly.

9. A weight of 200 lb. is supported by a rope. If the rope is drawn aside along *BC*, Fig. 170, by a force of 80 lb., find the tension in the rope.

10. The resultant of two equal forces acting at right angles upon an object is 120 lb. Find the magnitude of each force.

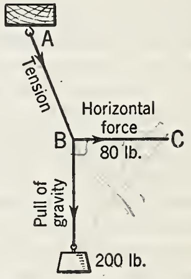
11. A man pushes with a force of 60 lb. against the handle of a lawn mower. If the handle makes an angle of 30° with the level of the ground, find both the horizontal and the vertical components of the 60-lb. force.

12. A picture is hung from a hook by means of a wire. The two divisions of the wire make an angle of 90° at the hook, and the tension in each one is 25 lb. Find the weight of the picture.

13. A person who weighs 160 lb. sits in the center of a hammock. The ropes supporting the hammock make angles of 60° with the posts to which they are attached. Find the tension on each rope.

14. A child weighing 100 lb. sits in a swing. Find the tension on the ropes when a man pushes against the swing with a force of 40 lb.

15. A child pulls upon a rope attached to a sled with a force of 30 lb. If the angle at which he pulls is 20° from the horizontal surface, what is the horizontal component of the force? What is the horizontal component of a force which a man exerts when he pulls with a force of 30 lb. on the same sled, but at an angle of 40°? Which one works to better advantage?



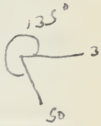


FIG. 170. Component of a force.

## 4. Parallel Forces

**143. What are parallel forces?** Two boys carry a load on a stick between them. Both boys are pulling in the same direction upon the stick, and the two forces are parallel to each other. They do not have the same point of application. Of course *the resultant of two parallel forces is equal to their sum*, if their direction is the same. Two horses pulling a loaded wagon furnish another example of parallel forces. The piers, or abutments, of a bridge both push up on opposite ends of the bridge, furnishing us with another example of parallel forces.

**144. What is the moment of a force?** Before we can understand how a load is distributed between two parallel forces, we need to understand what is meant by the *moment of a force*. Suppose that we have a rigid bar, *AB*, upon the ends of which two parallel forces, *F* and *F′*, are acting. The bar is free to turn about a fixed point, *C*, which is called the *center of moments*. The force *F* is really attempting to turn the bar *AB* about *C* in a clockwise direction, but the force *F′* tends to pull the bar around *C* in a counter-clockwise direction. How *effective* is each force? It can be shown by experiment that the effectiveness of any force in producing rotation, or the *moment of the force*, depends upon two things: 1. *The magnitude of the force;* 2. *The length of the arm upon which it acts.* Hence, *the moment of a force is equal to the product of the force times the length of the arm upon which it acts.* For example, a force *F* of 20 lb., acting upon the arm 4 ft. long, has a clockwise moment of 80. The force *F′* of 40 lb. acting upon the arm 2 ft. long has a counter-clockwise moment of 80. (See Fig. 171.)

If the force *F* is not applied perpendicularly to the bar *AB*, as shown in Fig. 172, then the length of the arm upon which the force acts is not *CB*, but it is equal to the perpendicular distance *d* from the line of direction of the force to the center of moments. The moment in such a case is equal to the product of the force *F* times the distance *d*.

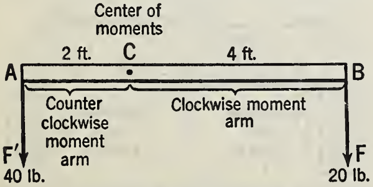


FIG. 171. Parallel forces.

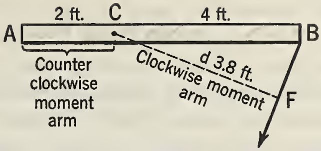


FIG. 172. The force acts at an acute angle.

**145. How do we use the principle of moments?** If two horses are pulling a loaded wagon and the hole in the doubletrees or evener upon which they pull is bored in the middle, then each horse must pull with the same force to move the load. If one horse is much stronger than the other, we make him pull more than 50% of the load by boring the hole in the doubletrees an inch or two from the center, and hitching the stronger horse to the shorter end of the doubletrees.

Two boys carry a load on a stick between them. (See Fig. 173.) The stick is 8 ft. long. The load, which weighs 160 lb., is placed 3 ft. from the boy at *A*, and 5 ft. from the boy at *B*. Let us inquire what part of the load each boy carries. To find the upward force the boy at *A* must use, let us consider that the hand of the boy at *B* acts as a center of moments. *A* is pulling up-

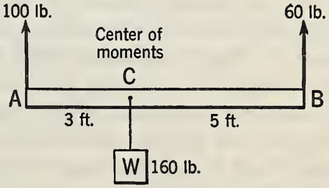


FIG. 173. How a load is apportioned between parallel forces.

ward (clockwise) upon an arm 8 ft. long. Let $x$ equal the force he exerts. Then the clockwise moment equals $8x$. But the load $W$ is pulling downward (counter-clockwise) with a force of 160 lb. upon an arm 5 ft. long. Its moment is $5 \times 160$, or 800. If the bar is in equilibrium, the two moments are equal. Then $8x = 800$. And $x$, the force at $A$, is 100 lb. To find the force needed by the boy at $B$, we assume that the center of moments is at $A$. Then the upward force, $x$, at $B$ acts counter-clockwise upon an arm 8 ft. long. The load, 160 lb., acts clockwise upon a 3 ft. arm. The moments are $8x$ and 480 respectively. Since $8x = 480$, then $x = 60$, the force at $B$. In these cases the weight of the stick was not considered.

The ends of a bridge pushing down upon the piers or abutments furnish another example of parallel forces. The force acting downward upon each pier is the same as the force needed to lift the end of the bridge at that pier. Suppose that the bridge $AB$ is 100 ft. long and that a weight of 10,000 lb. rests on the bridge 30 ft. from $A$., Fig. 174. Suppose we neglect the weight of the bridge. The clockwise moment at $A$ equals $100x$; the counter-clockwise moment of the weight on the bridge is $70 \times 10{,}000$, or 700,000. But these moments are equal. Hence, $100x = 700{,}000$, and $x = 7000$ lb. The number of pounds supported by pier $B$ is found in a similar manner. Using $A$ as the center of moments, we find that $100x = 30 \times 10{,}000$. Whence $x = 3000$ lb. If the weight of the bridge is distributed uniformly along its length, then each pier will support an additional weight equal to half the weight of the bridge. This force always acts upon the piers of the bridge.

**146. How can we find the equilibrant of two parallel forces?** To produce the same effect as two parallel forces, a single force or *resultant* must be equal to the sum of the forces. It must act in the *same* direction and it must be *applied at the center of moments.*

It follows, then, that the *equilibrant* of two parallel forces must also be equal to their *sum;* it must be *applied at the center of moments;* and it must act in the *opposite* direction to the resultant. Then the algebraic sum of the equilibrant and the resultant is *zero.* Of course the algebraic sum of the clockwise and counter-clockwise moments is also *zero.*

If the two parallel forces act in an opposite direction, then they tend to produce rotation. They are acting as a *couple.* In such a case, it is impossible to find any single force which will act as an equilibrant and produce equilibrium. Two hands applied to a steering wheel furnish an example.

In a later chapter we shall take up the study of the various types of machines. In all cases, we shall have to deal with several kinds of forces. In the first place, there is always an *acting force,* or *effort,* which is so applied to the machine that it attempts to produce motion. In the second place, there is always a *resisting force,* or *resistance,* which represents the load to be lifted or moved. Friction and weight of parts represent the other forces.

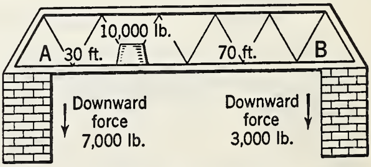


FIG. 174. Parallel piers support the bridge.

## 5. Center of Gravity and Equilibrium

**147. What is the center of gravity?** As a stone lies upon the ground, Fig. 175, the earth attracts every particle of it. All these downward forces which the earth exerts are parallel. Evidently the resultant of all these parallel forces is equal to their sum, which is the weight of the stone. The point of application of this resultant is called the *center of gravity*. The center of gravity of any object is that point at which *all its weight appears to be concentrated.* If we attach a string to a stone, at a point directly above the center of gravity, and pull upward, the stone can be lifted without any rotation. An object will balance on the point of a knife placed directly beneath its center of gravity. When we try to overturn the stone shown in the figure, the point *B* becomes the center of moments; *A* is the clockwise force acting upward, and the *whole weight* of the stone, concentrated at its center of gravity, acts counter-clockwise. If we consider *AB* as the arm upon which the effort acts, and *CB* as the arm upon which the weight acts, it is easy to understand why it is easier to overturn a stone than it is to lift it.

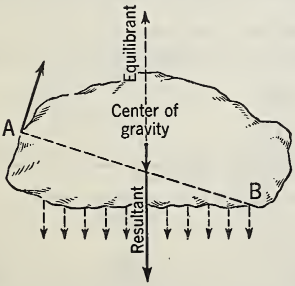


Fig. 175. All the weight appears to be concentrated at the center of gravity.

**★148. How can one find the center of gravity?** If we suspend a weight by means of a small cord, the line along which it will come to rest will, if produced downward, pass through the center of gravity of the earth. Such a weight and cord form a plumb line. If we wish to find experimentally the center of gravity of an irregular object, such as that shown in Fig. 176, we first suspend it from the point *P* in such a manner that it may turn freely about the point of suspension. The object will swing about this point and come to rest with its center of gravity directly below the point of support. Now if we drop a plumb line from the same point of support, the center of gravity of the object will coincide with some point in the plumb line. A line drawn along the plumb line must pass through this point. Next let us suspend the object from the point *B* and again draw a line in the direction indicated by the plumb

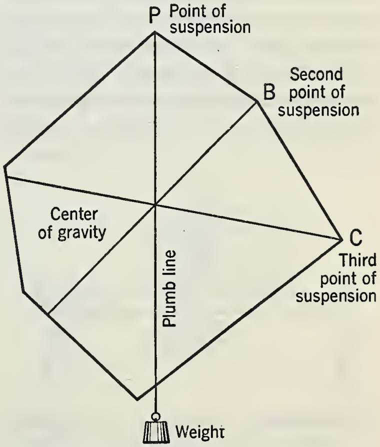


Fig. 176. How to find center of gravity experimentally.

line. For verification, we may repeat the operation, this time suspending the object from the point *C*. Each of these lines passes through the center of gravity. Therefore the center of gravity of the object lies at the point of intersection of these lines. In his work in mechanics, the student will find it very convenient to consider that *an object behaves as if all its weight were concentrated at its center of gravity.*

**149. How is equilibrium secured?** A book lying on a table pushes down upon the table with a force equal to its weight. The table must push upward with an equal force if the book remains in equilibrium. In order to keep the book or any other object in equilibrium, there must be no *unbalanced* force acting upon it. A push from one side must be balanced by an equal push from the opposite side. *An object is said to be in equilibrium when no unbalanced force acts upon it.* In other words, *the resultant of all the forces acting upon it is zero.*

To secure equilibrium, two kinds of motion must be prevented: *translatory*, or motion along a line; and *rotary*, or motion about a point acting as a pivot. Suppose that we have two parallel forces, *D* and *E*, of 80 and 120 lb. respectively, acting upon a bar at points *A* and *B*, Fig. 177. A force of 200 lb. applied in the opposite direction at *O* will prevent translatory motion, but it will not prevent rotary motion. Rotary motion may be prevented if the force of 200 lb. is applied at the center of moments, *x*, Fig. 178. Suppose the bar is 20 ft. long; then the equilibrant must be applied at a point 8 ft. from *B*, the greater force. The lengths of the arms upon which the two forces act are inversely proportional to the magnitude of the forces.

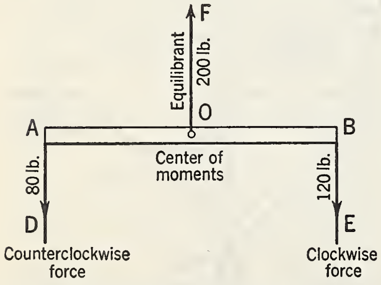


Fig. 177. The force at *F* prevents translatory motion.

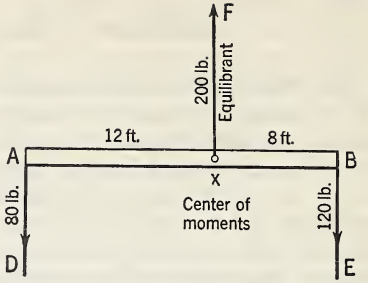


Fig. 178. The force at *X* produces equilibrium

Problem. A bar 30 ft. long is pivoted so that it is free to rotate about the point *C*, Fig. 179. At *A*, 6 ft. from *C*, a force of 400 lb. acts downward; at *B*, a force of 50 lb. acts downward; at *D*, 10 ft. from *C*, there is a downward force of 100 lb.; at *E*, 4 ft. from *B*, a force of 80 lb. acts upward; and at *F*, 2 ft. from *A*, a force of 250 lb. acts upward. Neglecting the weight of the bar, where must a force of 200 lb. be placed to secure equilibrium, and in what direction must it act?

*Solution.* The forces *B*, *D*, and *F* act clockwise; their distances from *C* (all dis-

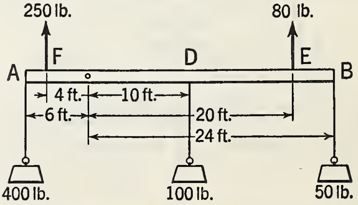


Fig. 179. The bar is in equilibrium when the algebraic sum of all the moments is zero.

tances must be measured from the center of moments) are 24, 10, and 4 ft. respectively. The forces $A$ and $E$ act counter-clockwise; their distances from $C$ are 6 and 20 ft. respectively. We solve the problem by finding the difference between the sums of the clockwise and counter-clockwise moments. Then we may let $x$ equal the distance that a 200-lb. force must be placed from $C$ to produce equilibrium. Its moment, $200x$, must equal the difference.

Clockwise moments

$$\begin{array}{r}
24 \times 50 = 1200 \\
10 \times 100 = 1000 \\
4 \times 250 = \underline{1000} \\
\text{sum} = 3200
\end{array}$$

Counter-clockwise moments

$$\begin{array}{r}
6 \times 400 = 2400 \\
20 \times 80 = \underline{1600} \\
\text{sum} = 4000 \\
\underline{3200} \\
\text{difference} = 800
\end{array}$$

Since $200x = 800$, then $x = 4$ ft., the distance from $C$ the 200-lb. force must be placed. Since the counter-clockwise forces are greater, it must be used as a clockwise force. Hence, it may act downward 4 ft. to the right of $C$, or upward 4 ft. to the left of $C$.

*Any number of parallel forces are in equilibrium if the sums of the opposite forces are equal, and the sums of all the clockwise moments are equal to the sums of all the counter-clockwise moments.*

**150. When is a body in stable equilibrium?** If an object is in stable equilibrium, it cannot be overturned without first raising its center of gravity. If slightly tipped, the object tends to return to its former position. The bricks shown in Fig. 180 are both in stable equilibrium, but their degree of stability differs. To overturn block ($A$) about the edge $P$, the center of gravity $C$ must be raised to the point $E$. When the center of gravity passes beyond the vertical line $EA$, so that it falls outside the area included within the base, the brick will be overturned and fall to the position shown by the dotted lines. The same brick, standing on end, Fig. 180$B$, is also in stable equilibrium, but it is not so hard to overturn it as when it lies flat on its side. In the position shown in Fig. 180$A$, the center of gravity must be lifted the vertical distance $EA$ before it can be overturned; in the position shown in Fig. 180$B$ the center of gravity must be lifted from $D$ to $E$ before it can be overturned. $EA$ is much greater than $ED$; hence the greater stability when the block lies on its side. *The stability of an object may be increased by enlarging the base and by having the center of gravity as low as possible.*

The base of support is represented roughly by the area inclosed by the perimeter drawn around the supporting members. The dotted lines of Fig. 181 inclose the area of the base. With a

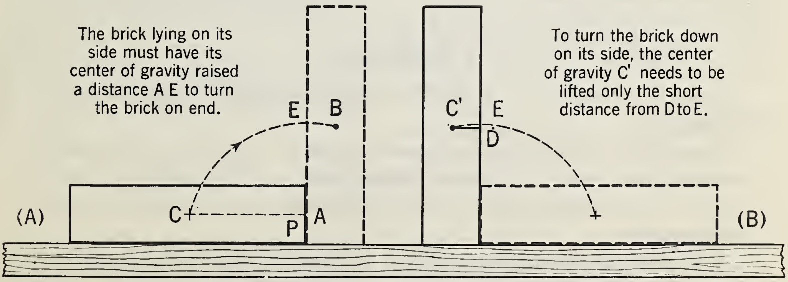

The brick lying on its side must have its center of gravity raised a distance A E to turn the brick on end.
E
B
C
A
P
(A)
C'
E
D
To turn the brick down on its side, the center of gravity C' needs to be lifted only the short distance from D to E.
(B)

FIG. 180. To stabilize an object we may broaden its base or lower its center of gravity.

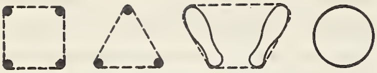


FIG. 181. Base of support.

three-legged stool the base is triangular; with an ordinary chair it is a rectangle.

A boat loaded with freight sinks very low in the water; at the same time the center of gravity is lowered, increasing its stability. A load of stone is less likely to be upset than one of hay, since the center of gravity of a load of stone is lower. In Fig. 182 the loaded truck on the sloping road will upset when the load is high enough to have its center of gravity at $C'$. A plumb line let fall from $C'$ falls outside the wheel base. If the top of the load is removed, the center of gravity is made lower. A plumb line let fall from $C$ falls within the area described by the wheel base, and the load is stable.

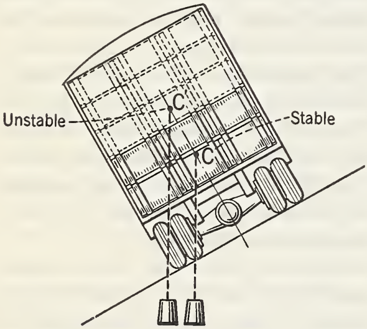


FIG. 182. The truck is stable when plumb line dropped from center of gravity falls within area described by base.

**151. When is a body in unstable equilibrium?** An egg standing on its end is in unstable equilibrium. A person walking a tightrope is another example. As soon as the slightest displacement occurs in either case, the center of gravity falls outside a plumb line perpendicular to the point of support; it begins to be lowered at once, and the object falls. In unstable equilibrium, the center of gravity is above the point of support.

**152. What is neutral equilibrium?** A ball lying on a table is in neutral equilibrium. A cylinder or a cone lying on its side, and a wheel free to turn upon its axle, are other examples of neutral equilibrium. Such objects come to rest in any position since the center of gravity is neither raised nor lowered when the object is overturned. (See Fig. 183.)

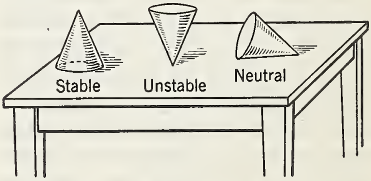


FIG. 183. Types of equilibrium.

## Summary

Force is a "push" or a "pull"; it tends to produce, change, or check motion.

Gravitation is the attraction between masses. The force of attraction between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

The gram of force and the pound of force are gravitational units of force. The dyne and the poundal are absolute units of force.

The resultant of two or more forces is that single force which could produce the same effect as two or more forces acting together. The resultant of forces acting in the same direction is their sum; the resultant of forces acting in opposite directions is their difference.

The resultant of two concurring forces acting at an angle is equal to the diagonal of the parallelogram of which the forces are adjacent sides. The equilibrant is that force which produces equilibrium; it is equal to the resultant and opposite in direction.

A single force may be resolved into two or more components. In such a case, the single force is represented by the diagonal of a parallelogram of which the two components are sides.

The center of gravity of a body is that point at which all its weight appears to be concentrated.

An object is in equilibrium when the resultant of all the forces acting upon it is zero. The stability of an object is increased by broadening its base and by lowering its center of gravity.

*How many of the following terms can you define or explain? (A wise man knows that he knows.)*

Galileo
Newton
Force
Gravitation
Law of gravitation
Units of force
Dyne
Poundal
Resultant
Equilibrant
Bernouilli's principle
Venturi meter
Moment of a force
Center of moments
Clockwise
Counter-clockwise
Center of gravity
Equilibrium
Composition of forces
Resolution of forces
Stability
Unstable equilibrium
Neutral equilibrium
Hydroplane

## QUESTIONS

1. In what two ways can a football guard increase his stability?

2. Compare a picture of a modern automobile with that of the early models. What are the advantages of the low, "underslung" models from the standpoint of stability? (See Figs. 184 and 185.)

3. Why does the oilcan shown in Fig. 186 right itself when placed on its side?

4. Why does a ball roll down hill?

5. Why does a man lean forward as he climbs a hill?

6. What type of equilibrium is exemplified by a person (*a*) standing in a canoe? (*b*) lying in the bottom of a canoe? (See Fig. 187.)

7. What is the purpose of ballast in an ocean vessel? Where is it placed?

8. It is difficult to balance a bowl on the end of a finger if the bowl is upright, but it is easy when the bowl is inverted. Explain.

9. A man has a tall, slender vase. In what two ways can he increase its stability?

10. Why does a tightrope walker carry a long pole?

11. Why are the Pyramids so stable?

12. A man carries a heavy bag on a stick swung over his shoulder. Explain why the handle of the bag should be kept close to his shoulder.

13. Is the center of gravity always within the object itself? (Consider a ring.)

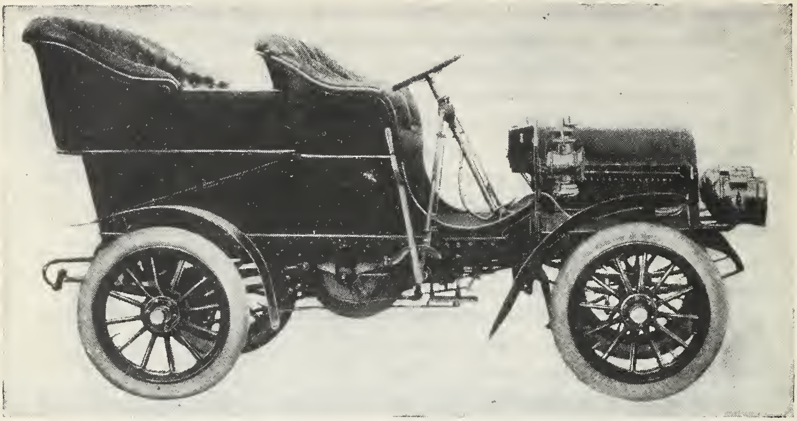
## PROBLEMS

### Group A

1. A wooden beam 16 ft. long weighs 300 lb. If the beam is uniform, what force is needed to pick up one end of the bar?

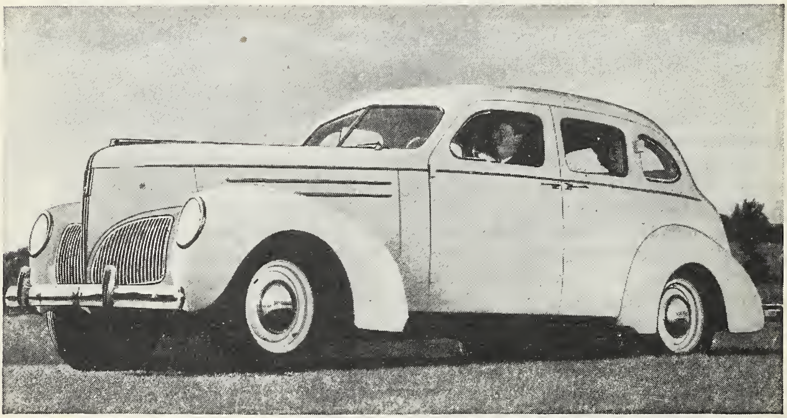
2. If the beam of Problem 1 is tapering and its center of gravity is 6 ft. from one end, what force is needed to pick up the large end? The small end?

3. Two boys carry a load of 150 lb. on a



*Courtesy of the Studebaker Corporation*

Fig. 184. Observe the high center of gravity of this obsolete model of 1904. The owner of such a car had no trouble in getting under his car to grease it or to make repairs. Ruts in the roads were often very deep, but there was plenty of room for road clearance.



*Courtesy of the Studebaker Corporation*

Fig. 185. The underslung chassis of the 1939 car lowers the center of gravity and promotes stability. From observation of this picture one can understand why hydraulic hoists have become so common at filling stations. Tremendous changes have taken place in automobile construction during the past 35 years.

stick 5 ft. long. If the load is 2 ft. from the larger boy, how much does each one carry?

4. A bridge is 400 ft. long. A load of 20 tons rests on the bridge at a distance of 80 ft. from one end. In addition to the weight of the bridge, what load does each pier sustain?

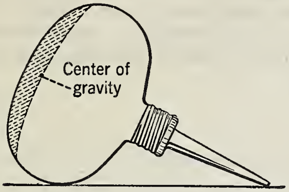

Center of gravity

FIG. 186. Why will can right itself?

5. A bridge 120 ft. long weighs 50 tons. An engine weighing 40 tons is crossing the bridge. What is the maximum load sustained by each pier? What is the minimum load? What is the load when the engine is 90 ft. from one end?

6. The doubletrees of Fig. 188 are 32 in. long. If a hole is bored 15 in. from one end, how many pounds does each horse pull, if hitched as shown in the figure to a load of 480 lb.?

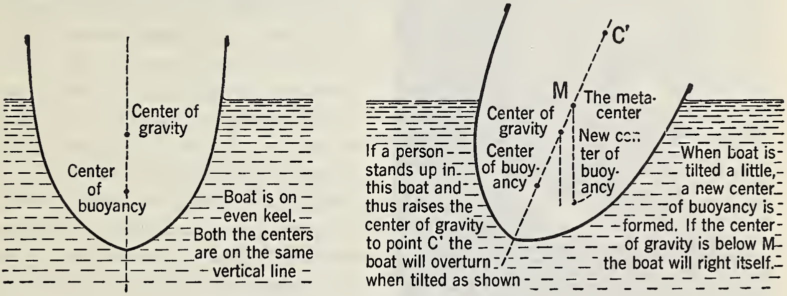

Center of gravity
Center of buoyancy
Boat is on even keel. Both the centers are on the same vertical line
C'
M
The meta-center
Center of gravity
Center of buoyancy
New center of buoyancy
If a person stands up in this boat and thus raises the center of gravity to point C' the boat will overturn when tilted as shown
When boat is tilted a little, a new center of buoyancy is formed. If the center of gravity is below M the boat will right itself.

FIG. 187. A canoe is not very stable.

## GROUP B

7. A painter's scaffold weighing 240 lb. is suspended by two parallel ropes 12 ft. apart. Find the tension on each rope. A painter weighing 180 lb. stands on the scaffold 1 ft. from one of the ropes. Find the tension on each rope. Find the tension on each rope when another painter weighing 168 lb. steps on the scaffold at a point 2 ft. from the other rope. (The student should draw a diagram. He may neglect weight of painter for simplicity.)

8. A pole is 30 ft. long and it weighs 1500 lb. Its center of gravity is 8 ft. from one end, and a bolt is put through the pole at a distance of 4 ft. from its center of gravity. At the large end of the pole there is a force of 400 lb. acting upward. How far from the other end of the pole must a boy who weighs 100 lb. sit in order to produce equilibrium?

9. A bar 12 ft. long has its center of gravity 3 ft. from one end. It just balances on the edge of a block placed 4 ft. from the smaller end when a weight of 80 lb. is applied to this end. Find the weight of the bar. (Consider that its entire weight is concentrated at its center of gravity.)

10. A man has a fish pole 10 ft. long which weighs 20 oz. He finds by balancing it on the edge of a board that its center of gravity is 30 in. from the larger end. He catches a fish and then finds that the pole with the fish attached as in Fig. 189 now balances in the middle. Find the weight of the fish.

11. A uniform pole 24 ft. long weighs 1000 lb. It is pivoted at a point 10 ft. from

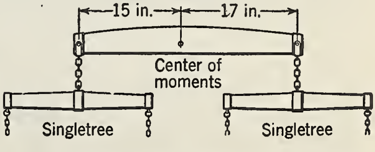

15 in.
17 in.
Center of moments
Singletree
Singletree

FIG. 188. The doubletrees furnish an example of parallel forces when used as an evener.

9

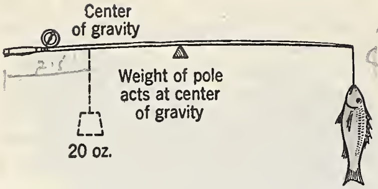

Center
of gravity
2'5'
Weight of pole
acts at center
of gravity
20 oz.

FIG. 189. Weight of pole concentrated at C. of G. counterbalances the fish.

the end *A*, from which a weight of 400 lb. is hung. At *B*, the other end of the pole, there is a weight of 600 lb. Two feet from B there is an upward force of 500 lb. Four feet from *A* there is an upward force of 800 lb. Where must a force of 600 lb. be applied to secure equilibrium, and in what direction does it act?

30

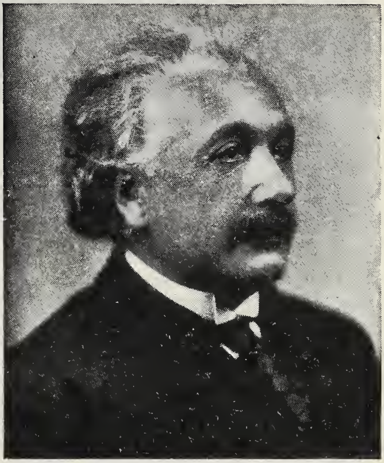
# Motion

## 1. Types of Motion

**153. What is motion?** *We may define motion as a change of place or position.* Both motion and rest are *relative* terms. A person may be riding uptown on one of the express trains of a New York subway. He is in motion with respect to an object on the station platform, but he is at rest with respect to others on the train. His train is passing an uptown local, to which the motion of his train is relative. There is a different example of relative motion, if we compare the motion of the uptown express with that of a downtown express or a downtown local. We appear to be at rest upon the surface of the earth, but as the earth rotates on its axis, we are carried with it at a speed of possibly 1000 miles per hour. We also travel with the earth in its path around the sun, a distance of a little more than 1,600,000 miles per day, at a speed of a little less than 70,000 miles per hour. (See Fig. 190.)

If an object moves in a straight line, its motion is said to be *rectilinear;* if the object moves along a curved line, its motion is *curvilinear.*

**154. Velocity is defined as the rate of motion.** The velocity of an object is the distance it moves in a given unit of time. It may be expressed in feet per second, miles per hour, kilometers per hour, etc. At a brisk walk we travel at a velocity of 5 or 6 ft. per sec., or about 4 mi. per hr. A sprinter runs at at the rate of 30 ft. per sec.; a train runs at a velocity of 60 mi. per hr. or



*Wide World*

FIG. 190. Albert Einstein (1879– ) proposed the theory of relativity. He is considered one of the foremost mathematicians in the world.

---

### Vocabulary

VELOCITY, rate of motion.

ACCELERATION, rate of change of velocity.

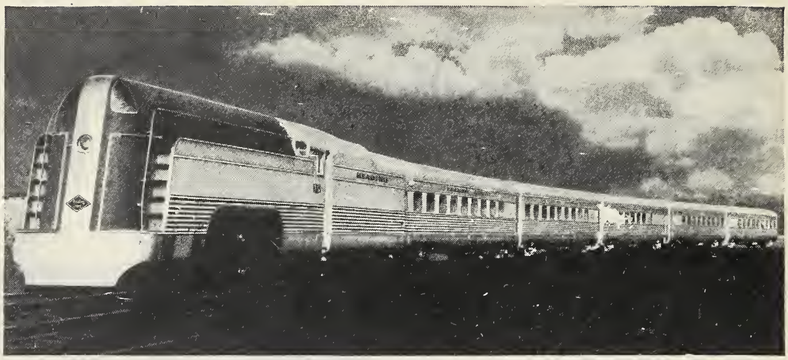
OSCILLATION, a backward and forward motion, or vibration.

MOMENTUM, the quantity of motion.

CENTRIFUGAL, pulling or reacting from the center.

CENTRIPETAL, directed or pulled toward the center.

LUBRICANT, a substance used to reduce friction



*Courtesy of the Reading Company*

FIG. 191. Streamlined trains attain greater speeds with less energy consumption.

88 ft. per sec. A rifle bullet may have a velocity of 3000 ft. per sec. The word "speed" is almost synonymous with the term "velocity," and they are often used interchangeably, although velocity more properly applies to the rate of motion in a given direction.

Motion is *uniform* when the velocity is constant, or when the distance a body moves is the same for each succeeding unit of time. A car that *maintains* a velocity of 30 mi. per hr. is an example of uniform motion. If a car travels 40 mi. the first hour, 20 mi. the second hour, and 30 mi. the third, its motion is *variable.* The distances it travels in equal periods of time are unequal. (See Fig. 191.)

**155. What is acceleration?** The word *accelerator* has grown more and more common with the increased use of the automobile. A man is driving at a velocity or speed of "30 miles per hour." He presses the accelerator, and increases his velocity to "40 miles per hour." He has *added to* his velocity "10 miles per hour." Such an *increase in velocity is called acceleration.* When a manufacturer advertises that his car will "accelerate from 5 miles per hour to 25 miles per hour in 8 seconds," he means that in 8 seconds 20 miles per hour can be added to the velocity of the car. That is an addition, or acceleration, of 2.5 miles per hour per second. A body that moves 1 ft. the first second, 3 ft. the next second, 5 ft. the third second, etc., furnishes an example of *accelerated motion.* In each second the velocity *increases* 2 ft. per sec., hence we say that the acceleration is 2 ft. *per second per second.* If a car moves 1 mi. per hr. the first second, 3 mi. per hr. the next second, and 5 mi. per hr. the third second, the increase in velocity for each second is 2 mi. per hr.; the acceleration is 2 mi. *per hr. per second.* Since in both of the examples given the acceleration is constant, the motion is *uniformly* accelerated. A body that moves 2 ft. the first second, 5 ft. the next second, and 10 ft. the third second is also an example of accelerated motion, but the acceleration is *not uniform;* it is *variably* accelerated motion, a type too common when some persons start cars in which others are riding.

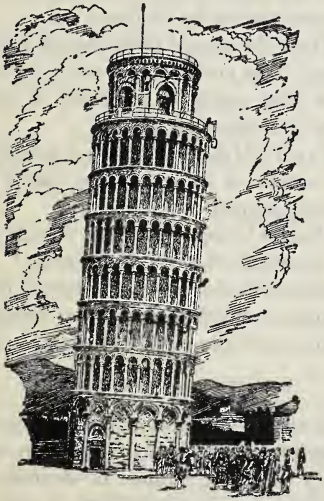
In stopping, a vehicle may move 7 ft., 5 ft., 3 ft., and 1 ft. in each of four

5

*successive seconds*. This is an example of *negatively accelerated* motion. It is also known as *retarded* or *decelerated* motion. Since in each second 2 ft. per second are *subtracted* from its velocity, its motion is *uniformly* retarded.

It is possible, too, to have *variably* retarded motion. We have an example of such motion when a reckless or unskilled driver rushes up to a red light and then stops with a screeching of brakes and tires.

**156. How can we find the velocity at any given time?** It is of interest to inquire what would happen if the acceleration stopped at the end of any *particular* second. For example, a car in starting moves 5, 10, 15, and 20 ft. per sec. for four successive seconds. Then the operator takes his foot off the accelerator. What happens? If we neglect friction, the car continues to move on at the *uniform* velocity of 20 ft. per sec. In accelerated motion, where the velocity varies each second, *the velocity at the end of any particular second is equal to the distance the body would move during the next second, if at that instant it ceased to be accelerated.*



*Courtesy of Popular Science Monthly*

Fig. 192. The leaning tower at Pisa, Italy, was the scene of some of Galileo's famous experiments.

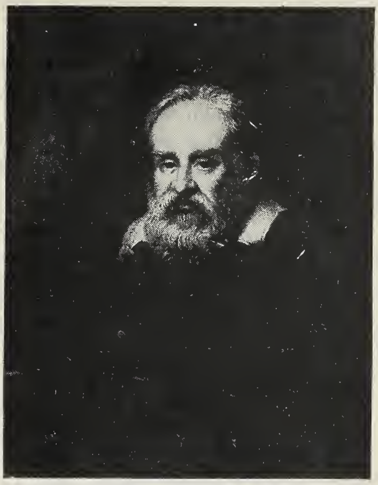


Fig. 193. Galileo Galilei (1564–1642) was an Italian physicist. At the age of eighteen, we find him observing the oscillations of a chandelier, and later formulating the laws of the pendulum. He gave us, too, the laws of accelerated motion and of falling bodies. He invented the practical telescope and constructed the air thermometer. He was one of the greatest of the world's scientists.

**157. What are the laws of accelerated motion?** Aristotle taught that the rate of fall of bodies was proportional to their weights. He said that a bundle of two bricks would fall twice as fast as a single brick. He did not experiment, and this false idea persisted for centuries. But Galileo was an experimenter. He dropped from the top of the leaning tower at Pisa objects of different material and found that they all reached the ground at nearly the same time. (See Fig. 192.) Even paper fell rapidly when rolled into a compact ball. Then Galileo used an inclined plane to study accelerated motion by rolling balls down the plane. A ball rolls down an inclined plane with uniformly accelerated motion, but the distance traveled in any number of seconds is so much less than that of freely falling bodies, that the distance can be more easily measured. (See Fig. 193.)

If we were to repeat his experiments by letting a ball roll down a grooved plane which is made just steep enough so that the ball rolls 1 ft. the first second, we should obtain results about as follows: (See Fig. 194.)

The ball rolls
1 foot in 1 second;
4 feet in 2 seconds;
9 feet in 3 seconds;
16 feet in 4 seconds;
25 feet in 5 seconds.

Thus we see that the distance the ball rolls is directly proportional to the square of the number of seconds. It is also easy to deduce the following observations:

The ball rolled
1 foot the *first* second;
3 feet the *second* second; (4–1)
5 feet the *third* second; (9–4)
7 feet the *fourth* second; (16–9)
9 feet the *fifth* second. (25–16)

The figures 1, 3, 5, 7, and 9 show that the motion was *uniformly* accelerated; the acceleration, *a*, is 2 feet per second for each second of time. Since velocity is the *rate* a body moves in a given time, and since acceleration is the *change in rate* for a given time, it is correct to use the term acceleration per second per second (rate per second of change of velocity), or acceleration per hour per hour. To avoid apparent repetition, the term "acceleration per second" may be used by the pupil when both the velocity and acceleration are rated in seconds. When a body starts from rest and travels with uniformly accelerated motion, *the acceleration equals twice the distance traversed during the first second.*

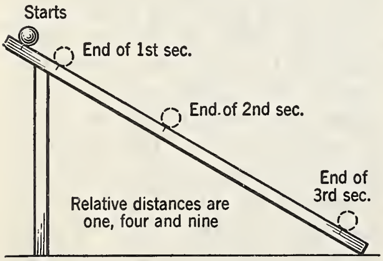


Fig. 194. The ball gains velocity as it rolls down the plane.

The *initial* velocity of the ball was zero; its acceleration, or gain in velocity, was 2 ft. per sec.; therefore its velocity at the *end* of the first second was 2 ft. per sec. At the end of the next second, its velocity was 4 ft. per second. In five seconds, 5 × 2, or 10 ft. per sec. will have been added to its original velocity. Its velocity at the end of the fifth second is 10 ft. per sec. Thus we find that in each case, the final velocity is equal to the *product of the acceleration by the time.*

From the simple observations given above, it is possible to deduce several laws that apply to all cases of uniformly accelerated motion.

Law 1. *If the acceleration is uniform, the velocity at the end of any second is directly proportional to the time.*

Using $v$ to represent *final* velocity, $a$ to represent acceleration, and $t$ to represent time, we may express this statement algebraically; *final velocity equals acceleration times the time.*

$$v = at. \qquad \text{(Formula 1)}$$

In all types of motion, the total space passed over, $S$, equals the *average* velocity times the number of seconds, $t$; or, *distance = average velocity × time.*

The average velocity for any given number of seconds equals one-half the sum of the initial and final velocities, or, average velocity =

$$\frac{\text{initial velocity} + \text{final velocity}}{2}.$$

For a body starting from rest, the initial velocity is zero; the final velocity equals *at;* from these values the second law may be derived:

$$\text{average velocity} = \frac{\text{zero} + at}{2},$$

whence we get by substitution in the formula, distance = average velocity × time, the following:

$$\text{distance} = \frac{at}{2} \times t, \text{ or}$$

$$S = \frac{1}{2}at^2. \quad \text{(Formula 2)}$$

LAW 2. *If the acceleration is constant, the distance traversed in any given number of seconds is equal to one-half the acceleration times the square of the number of seconds.*

In solving problems, we may use formula (1) to find $v$, $a$, or $t$, if two of these quantities are known. If any two of the following, $a$, $t$, and $S$, are known, the third may be found by the use of formula (2). Given $a$, $v$, and $S$; any two of them known, and the third to be found. Solving formula (1) for $t$, and substituting in formula (2) the value thus obtained, we get

$$v = \sqrt{2aS}. \quad \text{(Formula 3)}$$

The formula, $s = \frac{1}{2}a(2t - 1)$, may be used to find the distance traversed in any *given* second, the *sixth* or *eighth*, for example.

PROBLEM. A ball starting from rest rolls down an inclined plane with uniformly accelerated motion. If its acceleration is 20 ft. per second per second, find: (1), its velocity at the end of the tenth second; (2), the distance it travels in 10 seconds; and (3), the distance it rolls in the eighth second.

*Solution.* To find the final velocity, we use the formula, $v = at$. Whence, $v = 20 \times 10$, or 200 ft. per second. By substituting in the formula, $S = \frac{1}{2}at^2$, the values for $a$ and $t$, we have $S = \frac{1}{2} \times 20 \times (10).^2$ Whence, $S = 1000$ ft. To find the distance the ball rolls in the eighth second, we use the formula $s = \frac{1}{2}a(2t - 1)$. Whence,

$$s = 10[(2 \times 8) - 1]. \; s = 150 \text{ ft.}$$

*Alternative solution.* The final velocity is found from the formula $v = at$. Whence, $v = 200$ ft. per sec. The initial velocity is zero and the final velocity is 200 ft. per sec. The average velocity is 100 ft. per sec. In 10 seconds, the ball will roll 10 × 100 ft., or 1000 ft. In 8 seconds the ball rolls at an average velocity of 80 ft. per sec., a distance of 640 ft. In 7 seconds, the average velocity was 70 ft. per sec., and the distance 490 ft. In the *eighth* sec. it must have rolled the difference,

$$640–490 = 150 \text{ ft.}$$

**158. What are the laws for retarded motion?** The laws and formulas given in the preceding section also apply to *uniformly* retarded motion. We use them when we wish to know how far a car will run before it can be stopped, or how long it will take to stop a car. Suppose that we have a car traveling 30 mi. per hr., or 44 ft. per sec.; the brakes are capable of retarding the car 10 ft. per sec. per sec. We wish to know how quickly the car can be stopped and how far it will travel after the brakes are applied. Our problem is solved in exactly the same manner as if we asked how far a car must travel to attain a speed of 30 mi. per hr. if the acceleration is 10 ft. per sec. per sec., and how long it will take.

*Solution.* Velocity and acceleration are known; distance is to be found. These three quantities all occur in formula (3).

$$v = \sqrt{2aS}. \quad \text{(Formula 3)}$$

$$44 = \sqrt{2 \times 10 \times S}, \text{ by substitution.}$$

$$20S = (44)^2, \text{ and } S \text{ equals } 96.8 \text{ ft.}$$

To find the time, we may use $v = at$, and substitute $44 = 10t$, whence we find that $t = 4.4$, or we may substitute in the formula $S = \frac{1}{2}at^2$, using $S = 96.8$ ft. and

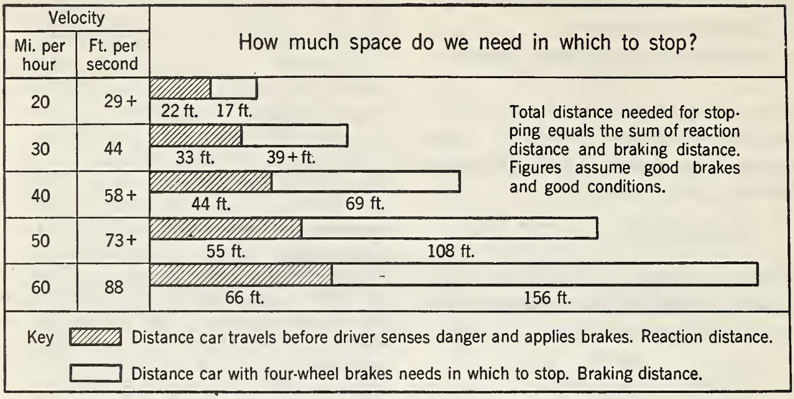


FIG. 195. Note that the doubling of the velocity requires four times the distance needed in which to stop a car.

$\frac{1}{2}a = 5$ ft. per second per second. The result is the same, 4.4 seconds.

The chart, Fig. 195, shows the distances within which a car should be able to stop when traveling at different velocities. It shows clearly that advertisements saying that a "car will stop on a dime" are untrue. For his own safety, the pupil should observe that a car needs *4 times the distance* in which to stop if the velocity is *doubled.*

**159. The laws of acceleration apply to freely falling bodies.** If we make the plane used in repeating Galileo's experiments steeper, the acceleration increases. When the plane is vertical, the ball becomes a freely falling body. The acceleration is due to the continuous attractive force of gravity, but now it is not resolved into two components as before. (See Fig. 153, Section 138.) The force of gravity pulls directly upon the ball.

We have learned that the "gram of force," which is a gravitational unit, imparts to 1 gm. of mass a velocity of 980 cm. per second in one second of time. Since $v = at$, then, from the above definition, $a$ is equal to 980 cm. per second per second at the latitude of New York.

The laws of accelerated motion apply to freely falling bodies, but since the *acceleration due to gravity* is always the same at a given locality, the letter $g$ is used instead of $a$ to represent acceleration. For New York, $g = 980$ cm., or 32.16 ft. per second per second. The formulas derived in Section 157 then become,

(1) $v = gt$
(2) $S = \frac{1}{2}gt^2$
(3) $v = \sqrt{2gS}$
(4) $s = \frac{1}{2}g(2t - 1)$.

**160. Objects fall at the same rate in a vacuum.** When Galileo performed his celebrated experiments with falling bodies, he found that dense objects fell rather more rapidly than lighter objects. There was so little difference in the majority of cases that he concluded that the unequal rate must be due to the resistance of the air, and *that all bodies would fall at the same rate in a vacuum.*

The invention of the air pump made it possible to prove the correctness of

Galileo's theory. A long glass tube, containing a feather and a coin, is inverted. The feather flutters down slowly, striking the bottom at a considerable interval after the coin. (See Fig. 196*A*.) When the air is pumped from the tube and it is again inverted, both fall simultaneously, (Fig. 196*B*). A man who weighs 200 lb. does not fall any faster than a man who weighs only 140 lb. A laboratory device known as the water hammer is sometimes used to demonstrate rapid fall in a vacuum. It consists of a glass tube partly filled with water; the air is removed and the tube sealed. When the tube is jerked suddenly, the water falls like a stone, producing a sharp click as it strikes the glass.

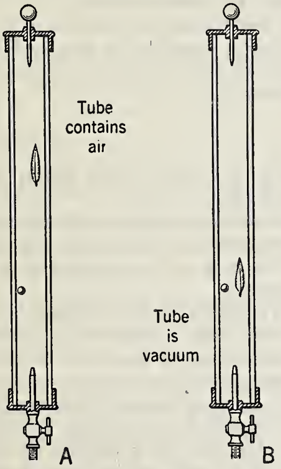


FIG. 196. Bodies fall at the same rate in a vacuum.

**★161. The laws of retardation and acceleration apply to bodies projected upward.** An object thrown upward is uniformly retarded until it finally stops rising. Then as it falls it is uniformly accelerated. If we know the initial velocity with which it is projected upward, we may apply the laws of accelerated motion to find how high it will rise, and how long a time will be required for the ascent.

PROBLEM. An object is projected upward with a velocity of 100 m. per sec. How high will it rise? How long a time will be needed for the ascent? How long a time will elapse before it strikes the earth?

*Solution.* In the formula, $v = \sqrt{2gS}$, $v$ and $g$ are known; $g = 980$ cm. per sec., or 9.8 m. per sec. Substituting, $100 = \sqrt{2 \times 9.8 \times S}$, whence $S = 510.2$m. From the formula, $v = gt$, we find the time required for the ascent, since $v$ and $g$ are known. Substituting, $100 = 9.8t$; whence $t = 10.2$ sec. Since it takes the same time for it to fall, it will be 20.4 sec. before it strikes the earth.

## QUESTIONS

1. Why does a parachute descend so slowly?

2. Give a reason why you would expect an object at the top of a tall mountain to fall more rapidly than at its base. Give a reason why you would expect it to fall less rapidly.

3. Does the speedometer of an automobile show velocity or acceleration? Explain.

4. Since the earth's attraction for a 5-lb. iron weight is five times as much as it is for a 1-lb. iron weight, why does not the 5-lb. weight fall five times as fast?

5. Water is poured from a pitcher at a height of a foot or more. Explain why the stream of water becomes much reduced in size.

6. If a car running 20 mi. per hr. can be stopped in 17 ft., what is the required stopping distance when the same car is traveling 40 mi. per hr.?

7. Compare the scientific accomplishments of Aristotle with those of Galileo.

8. Why is it necessary to give the acceleration due to gravity as 32.16 ft. per sec. per sec. at New York City? Is it the same at the Tropics?

## PROBLEMS

### GROUP A

In solving problems pertaining to freely falling bodies, use $g = 980$ cm. per second per second, or $g = 32$ ft. per second per second.

146.6 1. An airplane travels at a velocity of 100 mi. per hr. Express its velocity in ft. per sec.

217.09 2. Howard Hughes flew from New York to Paris, a distance of 3600 mi. in 16 hr. and 35 min. What was his speed in mi. per hr.?

65 3. In his round-the-world flight Hughes covered 14,548 miles in 91.5 hours, including time for refueling. What was his average speed in miles per minute?

4. In a motor-paced bicycle race, a rider covered a distance of 40 mi. in 55 min. What was his velocity in mi. per hr.? 43.6 In ft. per sec.? 4

168.96 5. A man runs 100 yd. in 9.6 sec. At that rate how long will it take him to run a mile? What is the record for the mile run?

40 sec 6. A train 550 yd. long runs at 45 mi. per hr. How long will it take the train to pass completely over a bridge 990 ft. long?

7. How far does a body fall in 15 sec.? With what velocity does it strike the earth?

8. How far does a body fall in 8 sec.? In 1 sec.? In $\frac{1}{2}$ sec.? In $\frac{1}{4}$ sec.?

9. How far does a body fall in 9 sec.? In the ninth second? Can you solve these problems by two methods? Do you get the same answers?

### GROUP B

10. A bomb is dropped from a height of 16,000 ft. How soon will it reach the earth?

11. With what velocity does the bomb of Problem 10 strike the earth?

12. The opening near the top of the Washington Monument is 504 ft. above the ground. With what velocity does a baseball tossed out of this opening strike the earth? Is it possible for a person to catch a baseball traveling at that velocity?

13. With what velocity must a ball be thrown upward to reach the top of the Empire State Building, 1248 ft. high?

14. How long from the time the ball of Problem 13 was thrown will it be before it again reaches the ground?

15. A batter drives a long fly ball to a height of 144 ft. If an outfielder can run at the rate of 25 ft. per sec., how much ground can he cover if he is to catch the ball?

16. An automobile running 30 mi. per hour can stop in 48 feet. What distance is needed to stop the same car when running 45 mi. per hr.?

17. A policeman steps into your car and asks you to drive at a speed of 20 mi. per hr. As you cross a white line, he signals you to stop. If you wish to stop within 22 ft., what retardation of the brakes is needed? How long will it take you to stop?

18. A train is running 60 mi. per hr. If the maximum retardation of the brakes is 5 ft. per sec. per sec., can the engineer stop the train in time to avoid hitting a car 600 ft. distant?

19. An object is thrown upward with a velocity of 50 m. per sec. How high will it rise? How long will it be before it strikes the ground?

20. The Eiffel Tower is about 300 m. high. With what velocity must an object be thrown to rise to the top of the tower? How long will it take to make the ascent?

21. A bombing plane is flying at an altitude of 10,000 ft. at a velocity of 120 mi. per hr. How long will it take for the bomb to fall? With what velocity does it strike the earth?

22. Assuming that the bomb moves forward at a speed of 120 mi. per hr. as it falls, how far beyond the vertical line from which it was dropped will it strike the earth? Can you see why it is difficult for bombers to score a hit?

23. A ball rolling down an inclined plane with uniformly accelerated motion moves 4 ft. the first second. Find: (*a*) its acceleration; (*b*) the length of the incline, if it takes 20 sec. for the ball to reach the bottom; and (*c*) its velocity at the end of the twentieth second.

24. A coaster going down hill travels 45 ft. during the fifth second. Find his acceleration. How far does he travel in 20 sec.? What will his velocity be at the end of the 20th sec.?

176/10 × 9.6/1 =

1056
1584
168.96

2.81
20 168.96
120
48 9

5.5' p.s.p.s.

## 2. The Pendulum

**162. What is a pendulum?** A body so suspended that it can swing to and fro about a horizontal axis is called a *pendulum*. The simple pendulum is defined as a particle so suspended by a *weightless cord*. Of course no such ideal pendulum can be constructed, but a ball suspended by a light thread is essentially a simple pendulum, Fig. 197. The point or axis about which a pendulum vibrates is called the *center of suspension*. As the ball or pendulum bob moves from *A* to *B*, it makes a *single vibration*. It makes a *complete vibration* as it moves from *A* to *B* and back again to *A*. The time required for a complete vibration is known as the *period* of the pendulum. The distance along the arc *AC* is known as the *amplitude* of vibration.

**163. What are the laws of the pendulum?** The student will recall that it was Galileo who began the experiments on air pressure which were later finished by Torricelli. Next we met this genius dropping objects of different density from the top of the leaning tower at Pisa. These simple experiments led to others from which Galileo developed the laws of accelerated motion and falling bodies. Now we see this philosopher as he sits in the cathedral in Pisa and watches a chandelier as it swings to and fro. With one finger on his pulse, he finds that successive vibrations are made in equal times. If this were not true, pendulums could not be used in clocks. Later he performed a series of experiments by means of which he ascertained several facts concerning the vibrations of the pendulum. These facts are known as the LAWS OF THE PENDULUM.

1. *The time of vibration is independent of the weight or material of the pendulum.* This law is strictly true only if the pendulum vibrates in a vacuum. The air resistance has more effect upon a ball of cotton used as a pendulum bob than it does upon a ball of lead.

2. *The time of vibration is independent of the amplitude, if the arc is small.* A pendulum usually swings through an arc of 10° or less.

3. *The time of vibration is directly proportional to the square root of the length of the pendulum.* This law may be expressed algebraically as follows:

$$t : t' = \sqrt{l} : \sqrt{l'}.$$

$t:t' = \sqrt{l}:$

If we have two pendulums, one 25 cm. long and the other 100 cm., the longer one will vibrate just half as fast as the shorter one. The square roots of 25 and 100 are 5 and 10 respectively. Hence the times required for one vibration are in the ratio of 5 to 10, or 1 to 2.

★4. *The period of vibration is inversely proportional to the square root of the acceleration due to gravity.* A pendulum vibrates rather more rapidly at the North Pole than at the equator. If we use the letter *l* to denote the length of a pendulum, and *g* to denote

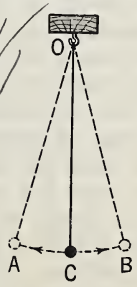


FIG. 197. The simple pendulum.

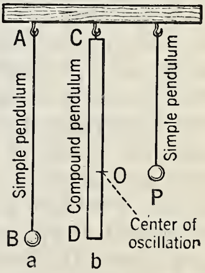


FIG. 198. The compound pendulum.

the acceleration due to gravity, then $t$, the time required for a single vibration, may be found by the following formula:

$$t = \pi\sqrt{\frac{l}{g}}.$$

Problem. Find the length of a pendulum that will make a single vibration in one second when $g$ equals 980 cm. per second per second.

*Solution.* Substituting the values, $t = 1$, and $g = 980$ cm., in the formula

$$t = \pi\sqrt{\frac{l}{g}}, \text{ or } t^2 = \frac{\pi^2 l}{g},$$

we have

$$1 = \frac{9.86965\,l}{980}, \text{ or } 9.86965\,l = 980 \text{ cm.}$$

Whence $l = 99.29$ cm., the length of a pendulum which will make a single vibration in one second at the latitude of New York, where $g = 980$ cm. per sec. per sec.

**★164. Where is the center of oscillation?** The length of the pendulum shown in Fig. 198*a* is measured from the point of suspension to the center of gravity of the ball *B*. A meter stick *CD* suspended from one end by a hook, although apparently of the same length as the pendulum *a*, does not vibrate at the same rate. It is a *compound* pendulum, Fig. 198*b*. Since its weight is distributed along its length, the several parts tend to vibrate as pendulums of different lengths. The particles near the lower end would, if isolated from the rest, vibrate more slowly. It is possible to find an intermediate particle, however, that would vibrate at the same rate as the undivided meter stick. This particle is at the *center of oscillation*. Experiment shows that the meter stick will vibrate at the same rate as the simple pendulum *P*, which is $\frac{2}{3}$ its length. If we bore a hole through the meter stick at the center of oscillation and suspend the meter stick from this point, it will have the same period as before. The real length of the meter stick swinging as a pendulum is the distance between the center of suspension and the center of oscillation.

**★165. Where is the center of percussion?** If we strike the meter stick at its center of oscillation with a mallet when it is suspended as in Fig. 198*b*, it will swing smoothly as a pendulum, without being jarred. If the meter stick is struck at any other point, it shivers or trembles instead of vibrating freely. The center of oscillation is coincident with the *center of percussion*. The center of percussion of a body is that point where a blow produces the least effect upon the center of suspension. A baseball player can drive a ball harder and farther if it strikes the bat at the center of percussion. If the ball strikes the bat at any other point, the bat "stings" the hands and is more likely to be broken. (See Fig. 199.)

Sometimes the handle of a hammer or ax is made too big for the weight of the head or blade. A woodsman, testing an ax that has too much wood in the handle says that the ax is poorly hung. Its center of percussion is in the handle when it should be in the ax itself.

**166. What are some uses of the pendulum?** The chief use of a pendulum is for keeping time. In a clock, the

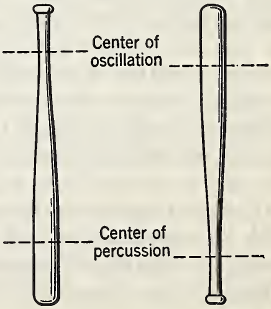


Fig. 199. The center of percussion.

movement of the hands is controlled by the swinging of a pendulum. In Fig. 200 the escapement wheel is one of a train of gear wheels that move the hands. Although these wheels are driven by a weight or spring, yet the escapement wheel is released one cog at a time by the vibrating pendulum, which thus indirectly controls the movement of the hands. A slight push from each cog as it escapes keeps the pendulum vibrating. A pendulum can be used to measure altitudes, but the barometer is more convenient. Foucault used a heavy pendulum bob suspended by a long wire to prove that the earth rotates on its axis. A stylus attached to the bob traced paths across a sanded curved floor. The pendulum vibrates in the same plane. Its tracings vary because the earth rotates.

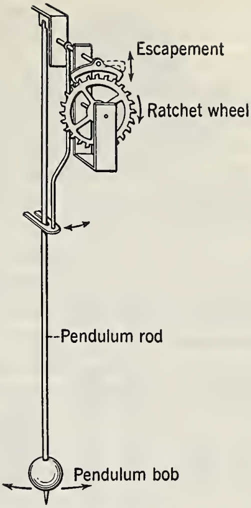


Fig. 200. The swinging of the pendulum releases the ratchet wheel.

## 3. Newton's Laws of Motion

**167. What are Newton's laws of motion?** Sir Isaac Newton formulated three laws of motion that help to explain some very important principles of physics. While they are not capable of complete demonstration, yet observation and experiment furnish evidence of their truth as applied to the motion of both terrestrial and celestial bodies. We have already seen *how* bodies move; NEWTON'S LAWS explain *why* bodies move. They deal with the relation between force and motion.

**168. What is Newton's first law?** *Every body continues in its state of rest or uniform motion in a straight line unless it is compelled by some external force to change that state.* This law is really a statement of the property of inertia, which was discussed in Section 16. No inanimate body can move or stop moving. A horse must pull very much harder to start a heavy load than to keep it moving; when started, however, it continues to move unless a backward force is applied to stop it. That an object tends to continue in motion in a *straight* line is clearly shown by the fact that mud flies from a rapidly rotating carriage wheel, or water from a grindstone along a line tangent to the circumference. If ice offered no resistance by friction, one who starts to slide on a lake of ice would continue to slide in a straight line entirely across the lake. Automobile drivers in rolling country sometimes coast down one hill and the inertia of the moving car will carry it part way up the hill on the opposite side of the valley. The practice, however, is dangerous.

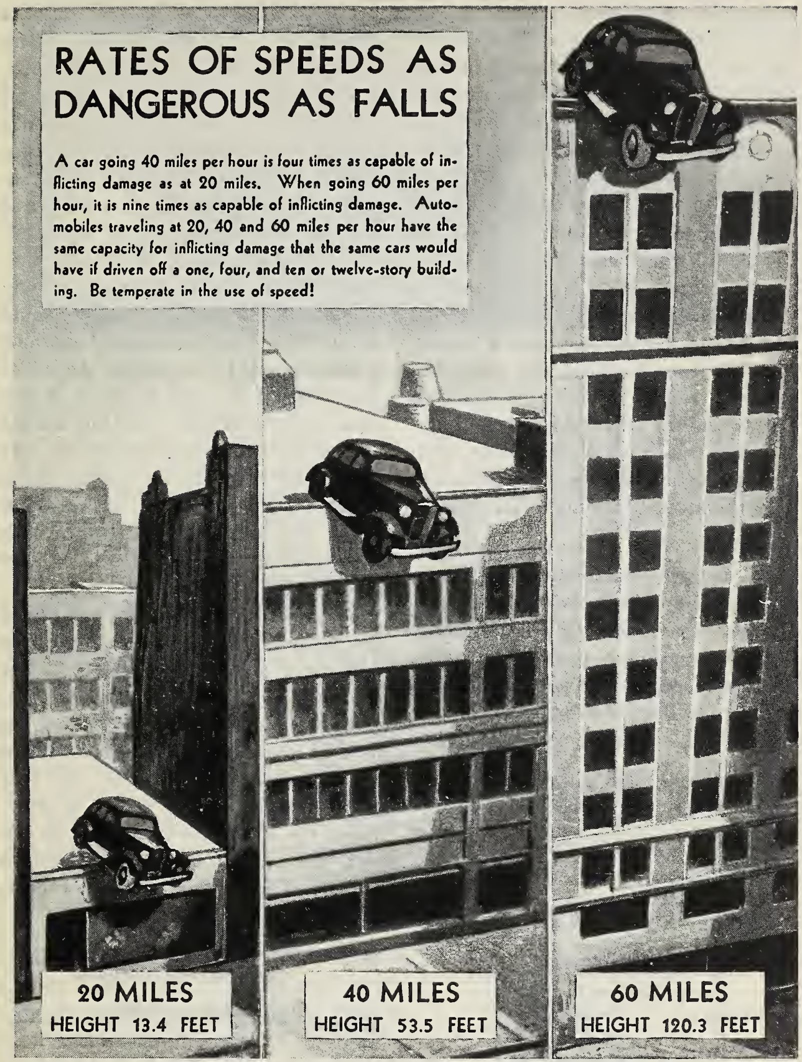
**169. What is momentum?** The student may place one hand flat on the table and lay a 1-lb. weight upon it. The effect is not unpleasant, but he may not care to continue the experiment by lifting the weight to a height of a foot or more and dropping it upon his hand. The impact in the second case is due to the *momentum* of the weight, or the product of its mass times its velocity. A ferryboat in docking moves very slowly, but a foot caught between the slowly moving boat and the dock would be crushed by the momentum of the boat. *This momentum is equal to the mass of the boat times its velocity.* A rifle bullet has terrific impact because its velocity is from 1500 to 3000 ft. per sec., and its small weight of a few ounces multiplied by such a high velocity gives a large momentum. A mass of 1 gm. moving with a velocity of 1 cm. per sec. has one unit of momentum (C.G.S.). A mass of 1 lb. moving with a velocity of 1 ft. per sec. has one unit of momentum (F.P.S.). A 2000-ton boat moving with a velocity of 20 ft. per sec. has a momentum of 80,000,000 units.

**170. How hard do we hit?** If we are walking only 4 ft. per sec. and collide with the edge of a door, we get a terrific jolt. A car running 20 mi. per hr. hits a tree. At 20 mi. per hr. its velocity is 29.3 ft. per sec. To gain that velocity a freely falling body would need to drop a trifle more than 13 feet. ($v = \sqrt{2gS}$.) Hence, you would get the same jolt by driving a car off a roof $13^+$ ft. high as you would by driving into a fixed object at 20 mi. per hr. Fig. 201 shows the effect of increased speeds upon impact.

It is possible to increase the momentum of a body by increasing its velocity. A larger force, acting upon a body for a short time, is needed to bring it up to a certain velocity than a smaller force acting for a longer time. The player who "follows through" on his golf or tennis stroke imparts greater velocity to the ball. A baseball player is more likely to knock a home run when he "follows through" than when he merely lets his bat "meet" the ball.

**171. What is the second law of motion.** Newton's first law states what happens to matter when forces *do not act* upon it; his second law is a statement of what does happen when forces *do act* upon it. If a force of 1 lb. acting upon a body produces a certain acceleration, a force of 2 lb. will produce double the acceleration. The second law may be stated as follows: *Rate of change of momentum is directly proportional to the acting force, and takes place in the direction in which the force acts.* The latter part of this statement is obvious, since experience teaches us that motion takes place in the direction of the force which produces it. If a ball thrown with a given force moves with a velocity of 50 ft. per sec., the force must be doubled to make the ball move with a velocity of 100 ft. per sec. From this law of motion, we may modify our definition of the dyne. *It is that force which, acting for one second upon any mass, imparts to it unit momentum.*

When two or more forces act together, each produces its own change of momentum, independently of the other forces. Thus the force that drives a bullet in a horizontal direction acts continuously; at the same time, the force of gravity is gradually pulling



RATES OF SPEEDS AS DANGEROUS AS FALLS

A car going 40 miles per hour is four times as capable of inflicting damage as at 20 miles. When going 60 miles per hour, it is nine times as capable of inflicting damage. Automobiles traveling at 20, 40 and 60 miles per hour have the same capacity for inflicting damage that the same cars would have if driven off a one, four, and ten or twelve-story building. Be temperate in the use of speed!

*Courtesy of the Travelers Insurance Company*

FIG. 201. At 40 miles per hour a car hits 4 times as hard as it does at 20 miles per hour. At 60 miles per hour the force of impact is 9 times as great. If two cars, each traveling 20 miles per hour, happen to meet head-on, the force of impact is the same as that which occurs when one car traveling 40 miles per hour hits a tree or a wall. What do you think your chance of survival would be if the car in which you were riding at 40 miles per hour should collide head-on with an oncoming car traveling 40 miles per hour? A booklet published by one of the accident insurance companies has for its title *Death Begins at Forty.* Your chance of escaping alive when an accident happens to your car traveling at high speeds becomes alarmingly small.

the bullet toward the earth. A ball dropped from the top of a tall tower strikes the ground at the same instant as a bullet fired horizontally from the top of the tower, although the latter may fall several thousand feet distant. (See Fig. 202.)

★If a force of 1 lb. acting upon a body produces an acceleration of 1 ft. per sec. per sec., then a force of 2 lb. acting upon the same body would impart to it an acceleration of 2 ft. per sec. per sec. *The acceleration is directly proportional to the acting force.* By using the letters $f$ and $f'$ to represent the two forces, and the letters $a$ and $a'$ to represent the respective accelerations, then we may include the above statement in a mathematical formula as follows:

$$f : f' = a : a'.$$

In the case of a freely falling body, one of the forces is known, because it is equal to the weight, $W$, of the body. The acceleration, $g$, is also known, because it is equal to the acceleration due to gravity. Then the formula becomes,

$$f : W = a : g.$$

By the use of this formula one can calculate the force needed to impart to a body of known weight any desired acceleration.

Problem. A car weighs 3000 lb. What force is needed to impart to it an acceleration of 10 ft. per sec. per sec.?

*Solution.* By substitution, we get,

$$f : 3000 = 10 : 32.$$

Whence, $f = 937.5$ lb.

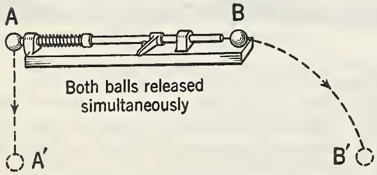


Fig. 202. Both balls strike the floor at the same instant.

**172. The path of a projectile is curved.** (*a*) *Fired horizontally.* Many persons have the idea that a rifle bullet fired horizontally travels in a straight line, but such is not the case. Gravity acts upon it immediately and constantly, pulling it from its course. Suppose its velocity is 3000 ft. per sec.; at the end of the first second, air resistance being ignored, it will have traveled 3000 ft.; but in 1 second a body falls 16.08 ft., and the bullet would strike 16.08 ft. below the point at which it was aimed. In 2 seconds the bullet travels 6000 ft., but it drops in the same interval 64.32 ft. (See Fig. 203*A*.) Of course, the greater the velocity, the more nearly the curve approaches a straight line. The curve of Fig. 203*B* shows the path of a ball thrown with a horizontal velocity of 100 ft. per second. (See Fig. 204.)

(*b*) *Fired at an angle.* In the use of the modern rifle, in which the bullet may have a velocity of 3000 ft. per second, the path of the bullet is so nearly horizontal that no correction need be made for *short* distances. When the object is more remote, the rear sight of the rifle is raised a trifle. When the rifle is then aimed at an object, the end of the barrel is raised slightly. The farther away the object,

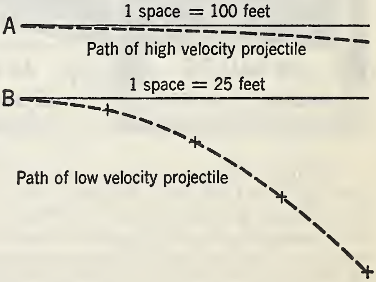
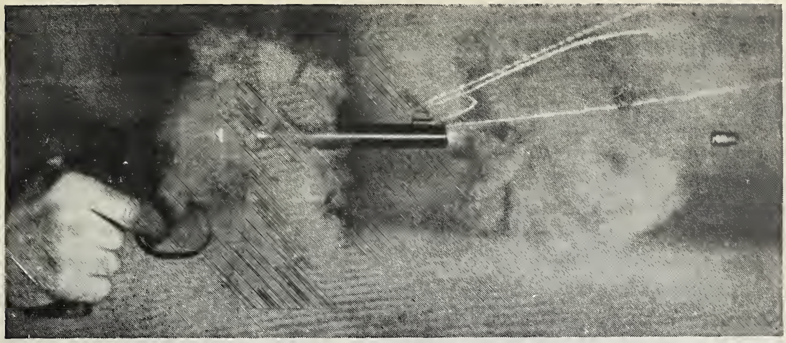

1 space = 100 feet
A
Path of high velocity projectile
1 space = 25 feet
B
Path of low velocity projectile

Fig. 203 *A*. Curve of a high velocity projectile. *B*. Curve of a low velocity projectile.



Courtesy of the Remington Arms Company. Inc.

FIG. 204. A pistol bullet photographed at the instant it left the pistol.

the more the rear sight is elevated before taking aim. The muzzle of a field gun is always elevated so that the projectile is fired at an angle. Fig. 205 shows the path such a projectile may take. The angle *BAC* is the *angle of elevation*. *AC* and *AD* are the component horizontal and vertical velocities, and *AR* is the *range*. The path *ABR* is called the *trajectory*. The higher the velocity of the projectile, the flatter the trajectory, Fig. 203. Under actual conditions, air resistance reduces the range, and corrections must be made for windage (deflection due to wind).

**173. We can find the composition of velocities.** From a consideration of the preceding paragraphs it is evident that we may have composition of velocities as well as composition of forces. Since it requires force to produce velocity, and we know that forces can be represented graphically, it seems reasonable to believe that velocities can be plotted in the same manner. In fact we can not only plot velocities, but we can also determine the resultant of two or more velocities acting concurrently. If a man rows a boat across a stream at a velocity of 4 miles per hour, and the current carries the boat downstream with a velocity of 4 miles per hour, we can find the *resultant* velocity by drawing the parallelogram shown in Fig. 206, and calculating the length of the diagonal. If the stream were 4 miles wide, the man would row across in an hour, but he would land 4 miles downstream, unless he kept the bow pointed somewhat upstream. He would actually have traveled along the diagonal of the parallelogram a distance of 5.66 miles $(\sqrt{(4)^2 + (4)^2} = 5.66)$.

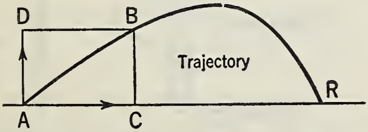


FIG. 205. Path of a projectile that is fired from an angle.

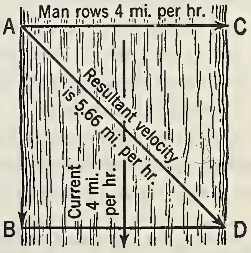


FIG. 206. Velocities are compounded just as we compound forces.

**174. What is Newton's third law?** A boy rows a boat toward the shore of a lake. When he is 3 or 4 feet from shore, he steps on the bow and attempts to leap ashore. The force with which he impels himself forward reacts and pushes the boat backward. The boy misses his mark and falls into the water. One who wishes to jump forward must stand on something fixed which resists this acting force. The end of a garden hose lying on the lawn is pushed backward by the reaction of the water as it issues from the nozzle. Water reacts against the oars of a boat and the arms of a swimmer; its reaction against the propellers makes the movement of a steamboat possible. The reaction of the air against the wings of a bird enables it to fly. The air reacts against the propellers of an airplane as they drive the plane forward, and the reaction against the plane is resolved into two components, one of which lifts the plane. (See Fig. 165.)

If we fasten one spring balance to the table, hook another spring balance to it as shown in Fig. 207, and pull steadily, it may be shown that the *reaction is equal to the action.* Both balances show the same reading. The collision balls of Fig. 208, may also be used to show that the force of reaction is *equal* to the action. If one ball is raised and let fall, one ball flies out at the opposite end of the line. When two balls are let fall, two balls at the other end of the line move in response to their action. Newton's third law is usually stated as follows: *To every action there is an equal and opposite reaction.*

Some have tried to argue that no motion can occur, if action and reaction are equal. But in reaction *two different* bodies are always involved. The water reacts against the oars, and the air against the propeller. If two boys pull upon a light wagon in opposite directions, the wagon moves in the direction of the greater force. Here *two forces* act upon *one body.* This is an example of *counteraction,* in which there is an *unbalanced* force. *Reaction* is shown by the fact that the earth reacts against the feet of each boy with a force which is exactly equal to the pull he exerts. The driving wheels of a moving automobile push backward on the

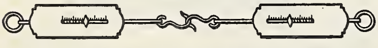


FIG. 207. Action equals reaction.

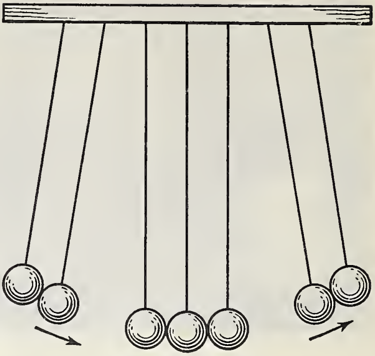


FIG. 208. Further proof that action equals reaction.

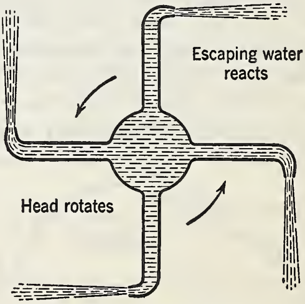
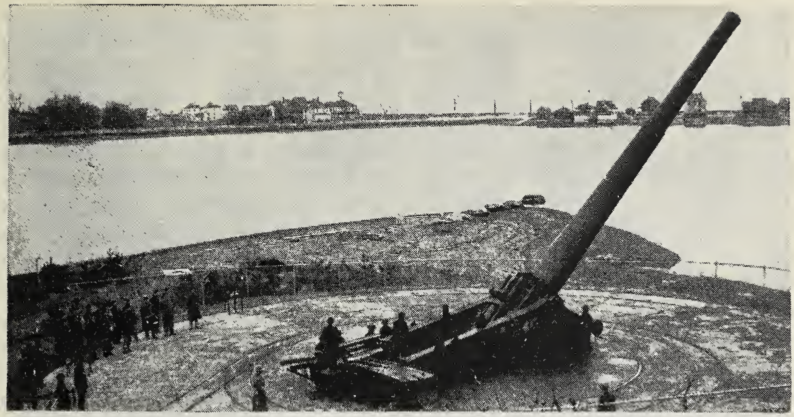


FIG. 209. Water escaping from nozzles reacts in a backward direction against them, thus producing rotation.



Courtesy of the War Department

FIG. 210. One of the modern guns installed at harbor fortifications for defense purposes. This is a 16-inch gun, and it can throw a projectile weighing a ton for a distance of over 20 miles. The recoil carries the gun backward.

ground, but the ground pushes forward on the wheels. This is reaction, but when this car tows another car the pull on the towline is an unbalanced force.

**175. What are some applications of reaction?** As the water issues from the nozzles of a *rotary lawn sprinkler*, the rotating head scatters the water in all directions. (See Fig. 209.) The recoil of a gun is sometimes used to eject the empty cartridges from rapid-fire guns. The recoil from some *disappearing* coast defense guns carries the gun back on its carriage and down behind the fortifications. (See Fig. 210.) Burning powder causes hot gases to be expelled from an ignited *sky rocket.* The force of reaction drives the rocket upward. So, too, the reacting force from expanding gases is used to drive *rocket bombs* with terrific force. The first *robot bomb* of World War II was kept on course by gyroscopes and driven at a speed of 350 mi. per hr. by the reacting force from a series of explosions, probably from gasoline and air. The reaction principle of exploding gases is finding use in rocket airplanes, especially for those planes that must get off the ground very quickly, or make high speeds.

## 4. Curvilinear Motion and Centrifugal Force

**176. How is curvilinear motion produced?** From Newton's first law we learned that a body which has acquired velocity continues to move in a straight line. If a second force acts upon the moving body at right angles to its path, it will be deflated from its rectilinear line, and its motion will become curvilinear. To illustrate, we may tie one end of a string to a ball. Holding the other end firmly, we may swing the ball in a circle about the hand as a center. The pull of the hand upon the cord deflects the ball away from its rectilinear path and toward the center. (See Fig. 211.) As the ball moves along the circumference from $B$ to $A$, the pull toward the center has deflected it a distance equal to $AO$. The constant pull that deflects a body from its rectilinear path and compels it to move along a curve, is called *centripetal* force (*centrum*, center; *petere*, to seek).

**177. What is centrifugal force** (*centrum*, center; *fugere*, to flee from)? If the revolving body of Fig. 211 did not have inertia, it would be pulled to the center. If the earth in revolving around the sun did not have inertia, it would fall into the sun. The reaction due to the inertia of the moving ball offers resistance to the centripetal pull and tends to break the string. If the string breaks, the ball immediately begins to move in a straight line along a tangent to the curved path. *The resistance that a moving body offers to deflection from a straight line is commonly known as centrifugal force.* Some physicists object to the use of the term "force" as applied to the tendency a body offers to resist being deflected from its path, but beginners find it easier to think of such reaction as *centrifugal force.*

**178. What are some illustrations of centrifugal force?** Mud flies from a rotating carriage wheel when the centrifugal force exceeds its adhesion to the tire. Water flies off at a tangent from a rapidly turning grindstone. David knew that a high velocity could be imparted to a missile by putting it in a sling and whirling it around his head. That knowledge and his skill in controlling the direction of the stone which he picked out of the brook made him the conqueror of Goliath. Emery wheels sometimes burst when driven at high velocity; the centrifugal force exceeds cohesion. An automobile rounding a curve at high speed is likely to "turn turtle." (See Fig. 212.)

**179. How can we counteract the effects of centrifugal force?** We lean toward the center when we are skating around a curve. To prevent the overturning of a train rounding a curve, the tracks are so banked that the rail on the outside of the curve is higher than the inside rail. Running tracks in gymnasiums and race tracks of all kinds are banked at curves to help nullify the effects of centrifugal force. Some of our new highways are banked at

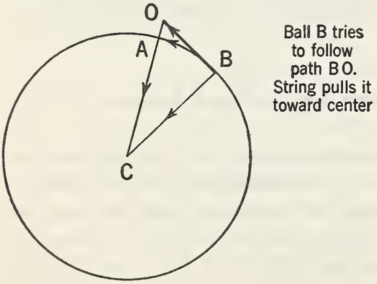

O
A
B
C
Ball B tries to follow path B O. String pulls it toward center

Fig. 211. The ball tends to break the string and follow the path *BO*

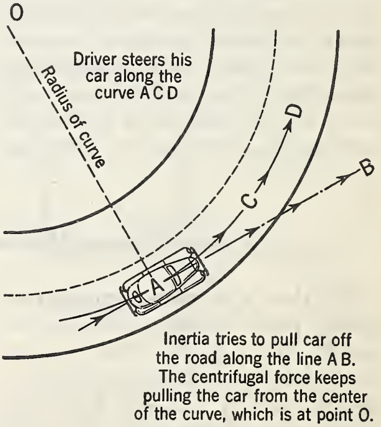
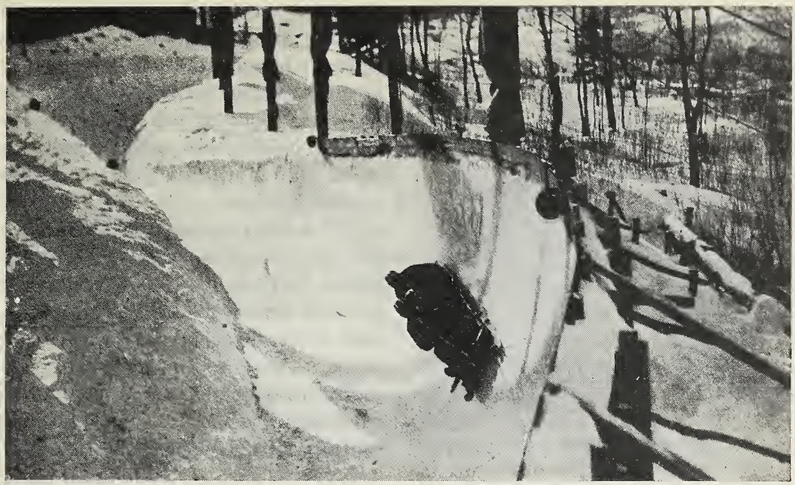

O
Driver steers his car along the curve A C D
Radius of curve
D
C
B
A
Inertia tries to pull car off the road along the line A B. The centrifugal force keeps pulling the car from the center of the curve, which is at point O.

Fig. 212. The centrifugal force is attempting to pull the car off the road.



Keystone View Company

Fig. 213. The bob-sled track is banked at the turns to help counteract centrifugal force. This picture taken at Lake Placid shows a sled almost perpendicular against a banked turn.

curves to help prevent accidents. Since centrifugal force depends upon inertia, and inertia is a general property of all matter, we cannot do away with centrifugal force, but we can in some cases prevent damage by nullifying its effects. (See Fig. 213.)

**180. What are some practical applications of centrifugal force?** In former years, farmers let the milk stand until the lighter cream rose to the top of the pan or crock. Then the cream was skimmed off the top of the milk. Now centrifugals are used to separate the cream from the milk. The milk enters the top of the separator, and is thrown against the surfaces of several funnel-shaped discs or blades that rotate at a high speed. The cream, which is lighter than the milk, rises along the top surfaces of the blades and issues from an opening near the center. (See Figs. 214 and 215.) The skim milk passes to the outside of the rotating blades where it is drawn off through a separate outlet.

James Watt devised a *governor* to regulate the speed of a stationary engine. It is operated by a belt driven from the shaft of the flywheel of the engine. As the speed increases, the two balls, Fig. 216, move farther apart,

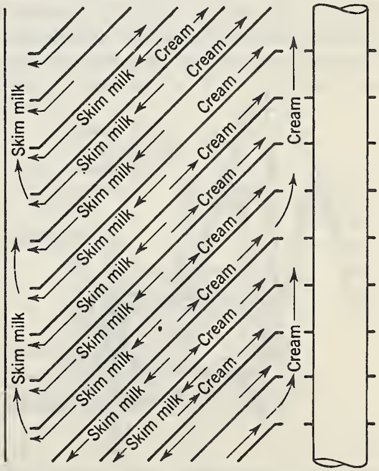
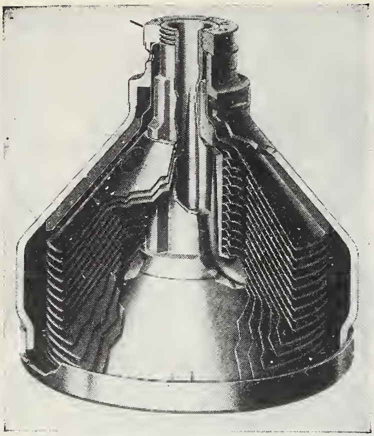

Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Skim milk
Cream
Cream
Cream
Cream
Cream
Cream
Cream
Cream
Cream
Cream
Cream

Fig. 214. The blades of the cream separator.



*Courtesy of the de Laval Separator Company*

Fig. 215. The whole milk enters at the top and is separated by centrifugal force. The blades, or discs, rotate at a speed of from 6000 to 8000 revolutions per minute. The skim milk, which is denser, is thrown against the lower surfaces of the discs, whence it passes down to the outer edge of the bowl. The cream, which is less dense than the milk, passes upward and inward toward the center.

since centrifugal force increases with the speed. As they move outward, they lift one end of a lever which shuts off some of the steam. The reverse occurs when the engine begins to slow down.

Some automobile *speedometers* are operated on a similar principle. Small weights are hinged to a shaft which is driven through a flexible cable by means of a gear attached to the drive shaft or to one of the wheels. As the speed increases these weights pull outward and move the pointer over a graduated dial.

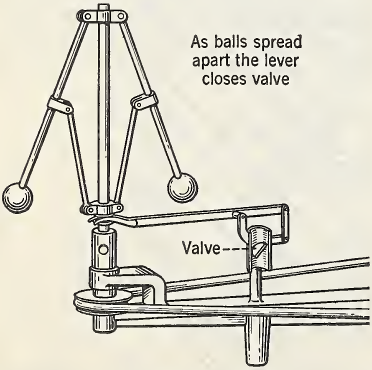


Fig. 216. Centrifugal force controls the governor and regulates the engine speed.

Wet solids may be partially dried by putting them in a perforated cylinder, which is then rapidly rotated. The water is thrown out through the openings. Crystals are dried in this manner; laundries also use this method for drying clothes. (See Fig. 217.) Some types of electric washing machines use the centrifuge for drying clothes.

A very efficient type of water pump depends for its action upon centrifugal force. (See Fig. 218.) As the rotor turns rapidly in the direction shown by the arrows, the water is forced by the rotating blades out through the discharge pipe.

Liquids that contain sediment are often centrifuged instead of being

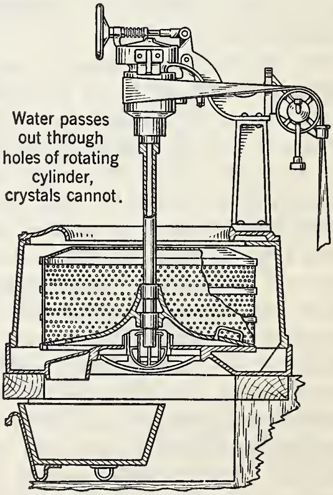

Water passes out through holes of rotating cylinder, crystals cannot.

Fig. 217. Centrifugals are used to dry clothes, crystals, and various chemicals.

filtered. The sediment from varnish is removed by this method. In making rayon, the solution of cotton must be passed through openings .005 mm. in diameter. As the solution of cotton flows into a solution of sodium hydroxide, a fiber is formed. It takes 20 of the small fibers thus produced to make a single thread of the silk. Since these openings are so very minute, the solution is centrifuged at 8000 or 10,000 revolutions per minute before spinning, in order to remove any sediment that might clog the openings. (See Fig. 219.)

Even our amusement parks utilize centrifugal force. At Coney Island the "human pool table" is an example. The "whip," the "loop-the-loop," etc., are other examples.

**★181. How can we calculate the magnitude of centrifugal force?** It is possible to measure the pull which the ball of Fig. 211, exerts upon the string. If we use a ball which has just double the mass, the pull on the string will be just twice as great. Hence we conclude that *the centrifugal force is directly proportional to the mass.* If we shorten the string, the ball is pulled from its path faster and it reacts with greater force to break the string. Careful measurements show that *centrifugal force is inversely proportional to the radius of curvature.* As we swing the ball faster, so that the velocity along the curve increases, it pulls more strongly on the cord. Accurate measurements show that the *centrifugal force is directly proportional to the square of the velocity.* If $v$ = velocity in centimeters per second, $m$ the mass in grams, and $r$ the radius in centimeters, then

$$\text{C.F. (in dynes)} = \frac{mv^2}{r}.$$

$$\text{C.F. (in gm.)} = \frac{mv^2}{gr}.$$

In the English system, if mass is in pounds, radius in feet, and velocity in feet per second, then

$$\text{C.F. (in poundals)} = \frac{mv^2}{r}.$$

$$\text{C.F. (in pounds)} = \frac{mv^2}{gr}.$$

PROBLEM. A ball that weighs 10 lb. is being rotated by means of a cord 4 ft. long. If its velocity is 20 ft. per second, find the force in pounds that tends to break the cord.

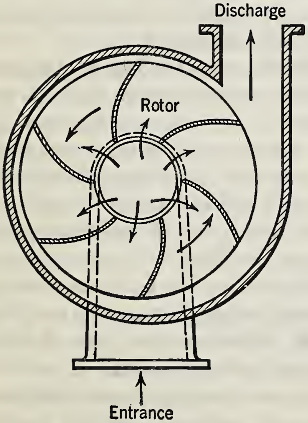


FIG. 218. The centrifugal pump is very efficient. Small ones are used to keep the water circulating through the cooling system of an automobile.

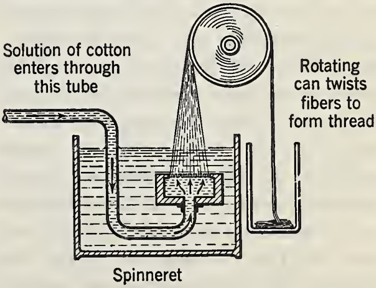

Solution of cotton enters through this tube
Rotating can twists fibers to form thread
Spinneret

FIG. 219. As the solution of cotton flows into the caustic solution through the tiny openings, it suddenly hardens into fine threads or filaments.

*Solution.* $v$, $g$, $r$, and $m$ are known. Substituting the values in the formula, C.F. $= \frac{mv^2}{gr}$, we get, C.F. $= \frac{10 \times (20)^2}{32 \times 4}$. Whence, C.F. = 31.25 lb.

**182. What is the principle of the gyroscope?** Everyone is familiar with the toy gyroscope and the spinning top. The centrifugal force of a heavy, rotating wheel gives it great stability. When such a wheel is rotating rapidly in a certain plane, considerable force must be used to change the plane of rotation. The principle of the gyroscope has been put to practical use in many ways. The Sperry type of stabilizer used on airplanes depends upon this principle. A gyroscopic compass is now used on all submarines. The flywheels on the engines of a steamship are mounted on axes that extend across the ship; thus they tend to prevent the rolling of the ship. The Italian liner *Conte di Savoia* is equipped with gyroscopes. The direction of a torpedo is also controlled by a gyroscope.

## 5. Friction

**183. What is friction?** *The resistance to any force trying to produce motion we call friction.* If we attempt to roll or slide one body over another, friction opposes us. To some extent it is due to adhesion, but it is largely caused by irregularities in the surfaces of the two bodies. Uneven surfaces tend to interlock and offer resistance to motion. Friction between smooth, plane surfaces is much less than it is between roughened surfaces.

**184. How does friction help us?** You have seen a driver trying to start a car on icy streets. The rear wheels spin around, but the car does not move. There must be friction between the tires and the pavement before one can start a car. A horse cannot pull a wagon unless friction furnishes him a secure foothold. Without friction, we would be unable to walk. It is difficult to walk on ice, but even the smoothest ice has some friction. When we apply the brakes to stop a moving car, we depend upon friction to aid us. The caterpillar tractor can pull heavy loads over soft ground or through the snow because the projections increase friction. (See Fig. 220.)

Friction also aids us in less obvious ways. We screw a hook into the ceiling. If there were no friction, it would immediately fall out of its own weight. Without friction, a nail driven into a board would not hold at all. Our dishes would slide off the table if the table were not perfectly level, provided friction were eliminated.

**185. How is friction a hindrance?** In those cases where an object is to be moved or where a resisting force is to be overcome, friction is a disadvantage. An axle upon which a wheel must turn is highly polished and then oiled to reduce friction. In all the bearings of a sewing machine, a bicycle, an automobile, or any other machine, efforts are made to reduce friction to a minimum.

**186. What are the laws of sliding friction between solids?** In scientific work, one depends upon experiment. By such methods, several so-called laws of *sliding friction* have been developed. In most cases they are only approximations, with many more ex-

FIG. 220. The caterpillar tractor utilizes friction in pulling its load.

ceptions than are common to most laws of physics.

1. If we hook a spring balance to an object, and pull horizontally, we find that it takes more force to start the object sliding than it does to keep it sliding. We conclude that *sliding friction is greater at starting.*

2. In a similar manner, we do not find that sliding friction is much greater if we run and pull a sled than it is if we walk along slowly. In such a case, we conclude that *sliding friction is independent of the velocity,* but it is a well-known fact that the friction of the brake shoes against the wheels of a train running 20 miles per hour is probably at least 50 per cent more than when the train is running 60 miles per hour.

3. If we have a brick lying on its side on a table, we find that the force needed to keep it sliding is almost the same as if the brick were lying on one edge or standing on end. Hence we conclude that *the force of friction is practically independent of the area of contact between the surfaces.* But in this case, too, a motorist finds that letting part of the air out of his tires will increase friction and reduce skidding because of increased area of contact. This may be partly due to the fact that the tires hold better because a part of the air is forced out from the space between them and the pavement, thus permitting air pressure to aid.

4. It does not require so much force to slide an empty chair across the floor as it does to slide the same chair when a 200-lb. man is sitting on it. *Friction is directly proportional to the weight of the object.*

**★187. What is the coefficient of friction?** Let us weigh a block of wood and then hook a spring balance to it so that it may be pulled along the table. (See Fig. 221.) The reading of the spring balance is much less than the weight of the block. It takes less force to slide one end of a piano than it does to lift it. The ratio of this "force of friction" to the weight of the block is called the *coefficient of friction.*

$$\text{C.F.} = \frac{\text{force to overcome friction}}{\text{weight}}.$$

Suppose that the block weighs 100 gm., and it needs a force of only 30 grams to keep the block in uniform motion. Then the coefficient of friction is $\frac{30}{100}$, or 0.3. The coefficient of friction varies with the nature of the material and the degree of polish of the surface. The coefficient of friction of iron sliding on iron is less than that of wood sliding on wood.

**188. Fluid friction is less than solid friction.** Everyone knows that an automobile "skids" more easily on a wet pavement than it does on one that is dry. We know that oil makes a machine run more easily. It is generally true that *fluid* friction is much less than *solid* friction. To show the difference one might try rowing a boat in the water and then try to row the boat over the sand on the beach.

While sliding friction is fairly independent of velocity, fluid friction varies greatly with the velocity. At moderate speeds fluid friction is nearly proportional to the square of the velocity. The railroad companies charge a higher fare on fast trains because it costs more to operate them at high speed. The air resistance increases with an increase of velocity. It is estimated that a modern automobile traveling 40 mi. per hr. uses over 7% of its fuel energy in overcoming air resistance. At 20 mi. per hr., the air resistance is only one-fourth as much. An ocean liner of the *George Washington* type, which crosses the Atlantic in 10 days, can afford to carry passengers at a lower rate than the *Queen Mary*, which makes the trip in 4.5 days, despite the fact that the passengers have to be fed for twice as many days. A destroyer may be only one-tenth as heavy as a modern battleship, but its engines must develop nearly as much horsepower, since its speed is 15 or more knots per hour greater.

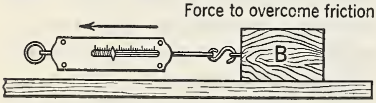


Fig. 221. Measuring the force needed to overcome sliding friction.

**189. How can we increase friction?** The engineer of a locomotive sands the rails so that the drive wheels will not slip. Sand is used on street car tracks and icy hills in winter. Chains are put on the rear wheels of automobiles to enable the tires to "grip" the pavement without skidding. In various sports and occupations, men wear rubber-soled shoes or have the soles studded with "spikes" or "cleats" to prevent slipping. The violonist rosins his bow to increase friction, and a baseball pitcher dips his fingers into a rosin bag to enable him to get a better grip on the ball. The brakes of automobiles are lined with material which has a high coefficient of friction. (See Fig. 222.)

**190. How can we reduce friction?** Several methods of reducing friction are in common use. To have a machine that is free-running and has little friction, the manufacturer or the operator

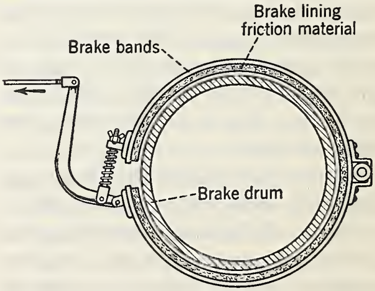


Fig. 222. Brake bands are lined with friction material. They stop a car by contracting around the brake drum, or by expanding against the inner rim of the drum.

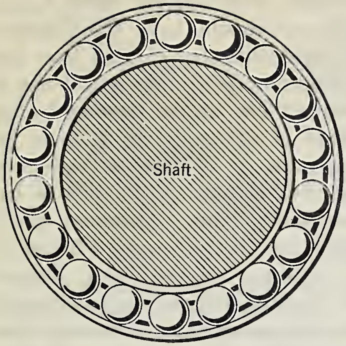


FIG. 223. Ball bearings are used to reduce friction.

may do one or more of the following things:

1. *Polish the bearings.* If a wheel is to turn easily on an axle, both the contact surfaces must be polished to a glass-like smoothness. The material, too, must be so hard that it will not wear away rapidly or become grooved easily.

2. *Use anti-friction metals.* When steel slides over an alloy of lead and antimony, the coefficient of friction is less than when steel slides on steel. Bearings are sometimes packed with such an alloy to reduce friction. The alloy is known as *anti-friction metal,* and the process is called *babbitting,* from the inventor, Babbitt.

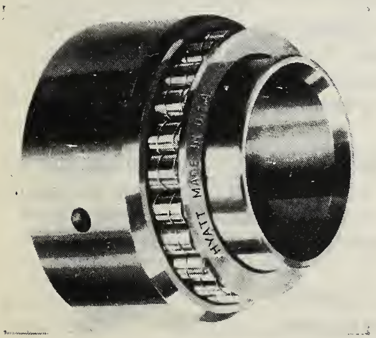

*Courtesy of the Hyatt Roller Bearing Company*

FIG. 224. Flexible roller bearings are used to reduce friction.

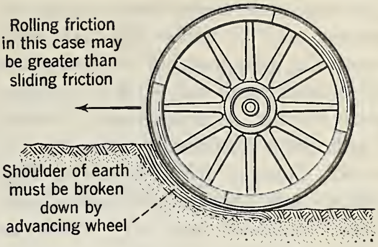

Rolling friction in this case may be greater than sliding friction
Shoulder of earth must be broken down by advancing wheel

FIG. 225. Rolling friction in some cases is very great.

3. *Use ball bearings or roller bearings.* The coefficient of friction of steel balls rolling on steel may be as low as 0.002, only about 0.01 as much as that of steel sliding on steel. We put casters on beds and other furniture to make use of rolling friction. (See Figs. 223 and 224.) If one surface is soft, then rolling friction may be high. A sled may slide over

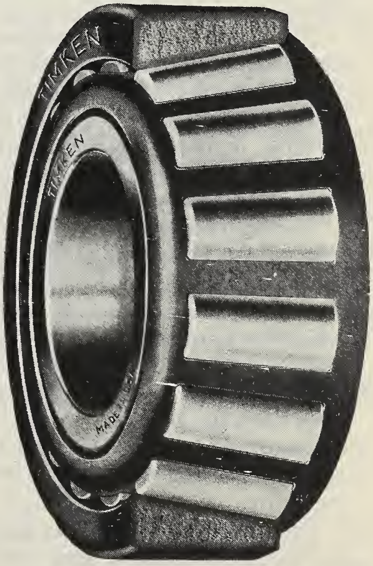

*Courtesy of the Timken Roller Bearing Company*

FIG. 226. The tapered roller bearing makes a strong bearing of low friction.

the snow more easily than a vehicle on wheels may be pulled through deep snow. Fig. 225 shows how a wheel which sinks deeply into soft earth encounters great friction. As it advances, it has to break down continually a shoulder of earth. Tapered roller bearings, Fig. 226, are much used in automobile bearings. They are especially strong in resisting sidewise thrusts.

4. *Use a lubricant.* If oil, for example, is used as a lubricant, an oil film flows between the bearing surfaces, separating them so that *fluid* friction is substituted for *solid* friction. The common lubricants include oils, grease, graphite, and wax. Paraffin and soap are good lubricants for wood. A good lubricant should have the following characteristics: (*a*) It must have just sufficient body so that it will not be squeezed out of the bearing by the weight of the parts. (*b*) It must not evaporate. (*c*) It must not corrode or rust the bearings. (*d*) It must be free from hard, gritty substances. (*e*) It should not be too much affected by temperature. It is possible to judge of the viscosity of oils for use as lubricants by letting metal balls fall through tubes filled with the oils to be tested. The thickness of the oil can be judged by the amount of time it takes for the balls to fall through the different oil samples.

## Summary

Motion may be rectilinear or curvilinear. Velocity is the rate of motion. Acceleration is the rate of change of velocity.

If the acceleration is constant, velocity = acceleration × time; space passed over $= \frac{1}{2} at^2$.

The laws of accelerated motion apply to uniformly retarded motion. Freely falling bodies are uniformly accelerated. The acceleration, which is due to gravity, is approximately 980 cm. per second per second.

The period of vibration of the pendulum is independent of the mass, material, or amplitude; it is directly proportional to the square root of the length, and inversely proportional to the square root of the acceleration due to gravity.

Newton formulated three laws of motion: Every body continues in its state of rest or uniform motion in a straight line unless compelled by some external force to change that state. Rate of change of momentum is proportional to the acting force and takes place in the direction in which the force acts. For every action there is an equal and opposite reaction.

Momentum is the quantity of motion. It equals the product of the mass times the velocity.

Centrifugal force increases with the mass; it is directly proportional to the square of the velocity; it is inversely proportional to the radius of curvature.

Friction, or the resistance to motion, is generally greater in solids than in fluids. Lubricants are used to reduce friction.

*How many of the following terms can you define or explain? (What is your rating?)*

Motion
Velocity
Acceleration
Laws of accelerated motion
Retarded motion
Laws of falling bodies
Pendulum
Laws of pendulum
Oscillation
Percussion
Newton's laws of motion
Momentum
Composition of velocities
Reaction
Centrifugal force
Laws of centrifugal force
Friction
Gyroscope
Coefficient of friction
Lubrication
Rolling friction

## QUESTIONS

1. If a clock gains time, would you raise or lower the pendulum bob? Explain.

2. Does a pendulum vibrate faster at the top of a mountain or at its base? Give a reason for your answer.

3. A string fastened to a hook can just support a weight of 50 lb. If two boys pull at opposite ends of this string when the weight is removed, how much must each pull to break the string? Explain.

4. Explain the principle of the rotary lawn sprinkler.

5. If action equals reaction, why is it not as dangerous to receive the "kick" of a gun as to be struck by the bullet?

6. Why is the head of a hammer tightened by pounding on the end of the handle?

7. Why do farm wagons often have tires from 3 to 5 inches wide?

8. How does centrifugal force affect the weight of objects at the equator?

9. A hammer sometimes "stings" the hand. Explain.

10. How would you locate the center of percussion of a baseball bat?

11. How do the bicycle and motorcycle illustrate the gyroscopic principle?

12. Could David have thrown a stone farther with a 3-ft. or a 4-ft. cord attached to his sling? Explain.

13. If a man is strong enough to swing a 5-ft. baseball bat, can he drive a ball farther with it than with a bat of the usual length? If so, why not use such a bat?

14. Other things being equal, does a long-armed baseball pitcher have an advantage over his shorter-armed opponent?

15. What are the characteristics of a good lubricant? What kind would you select for the axle of a motor truck? For the wheels of your watch?

16. Why do automobile drivers use a different kind of oil in winter than that used in summer?

17. What do manufacturers mean by a "non-skid" tire?

18. What advantages does the "caterpillar" tractor shown in Fig. 220 have?

19. Why are jewels used in the bearings of high-grade watches?

20. Machines used to assort balls for bearings are accurate to 0.00005 in. Why must the degree of accuracy be so high?

21. Try to find out what oil is used for lubricating airplane engines and explain why.

22. How would you proceed to spin a cotton thread without the use of friction?

23. What would happen to a knot tied in a rope if friction were eliminated? What would happen to the rope?

24. Explain why a sharp curve of short radius is more dangerous to the driver of a car than a curve of long radius?

25. Why does it take 50% more gasoline to run a car at 60 miles per hour than it does to run the same car at 40 miles per hour? Why can one save more than 50% in gasoline by driving at 20 miles per hour instead of at 40 miles per hour?

26. Why does rounding a car at high speed waste rubber by shearing it off on the surface of the roadway?

27. Why do sudden stops and jack-rabbit starts waste gasoline and wear out tires rapidly?

28. What arguments can you give for a national law permitting a maximum speed of not more than 35 miles per hour on our highways?

## PROBLEMS

### Group A

1. If a pendulum 16 cm. long makes a single vibration in 0.4 second, how long will it take for a pendulum 49 cm. long to vibrate?

2. It takes a force of 40 lb. to keep a 1000-lb. roller moving. What is the coefficient of friction?

3. A man who weighs 180 lb. runs with a speed of 20 ft. per second. A second man who weighs 140 lb. runs at a speed of 30 ft. per second. What is the momentum of each one?

4. One pendulum makes a vibration in 0.5 sec., and another pendulum makes a vibration in 0.9 sec. How do their lengths compare?

5. The weight on the drive wheels of a locomotive is 60 tons. If the coefficient of friction between the wheels and the track is 0.2, how great a pull can the engine exert upon the train? If the coefficient of friction is increased to 0.4 by sanding the track, what is the maximum pull of the engine?

6. If a force of 20 lb. is needed to pull a sled weighing 200 lb. over the ice, what is the coefficient of friction?

### Group B

7. How long must a pendulum be to make a single vibration in 0.5 sec., if $g$ equals 980 cm. per sec. per sec.?

8. A ball weighing 16 lb. is swung by a cord 4 ft. long. If the velocity is 20 ft. per sec., what pull in pounds does it exert on the cord?

9. A car weighing 3600 lb. rounds a curve of 80-ft. radius at 20 mi. per hr. What is the force in lb. tending to throw the car off the road?

10. If the car of Problem 9 rounds the curve at a speed of 45 mi. per hr., what is the centrifugal force in pounds?

11. Suppose that the car of Problem 9 is traveling 60 mi. per hr. around the curve. What is the centrifugal force in pounds? How much would you need to lengthen the radius in order to reduce the centrifugal force down to the weight of the car?

12. A ball dropped falls in just two seconds. A ball thrown upward at exactly the same time rises for two seconds. How high above the ground do they meet?

13. A 12-lb. ball is fastened to one end of a wire 4 ft. long. A person holding the other end swings the ball in a circle at the rate of 2 revolutions per second. What is the pull in pounds that the ball exerts?

14. A projectile fired horizontally weighs 1000 lb. What force is needed to give it an acceleration of 20 ft. per second per second?

15. A force of 40 lb. acts upon a body which weighs 200 lb. What acceleration per second per second is imparted to the body if $g$ equals 32 ft. per sec. per sec.?

# Unit Four

# *Work — Power — Energy*

## Preview

IN THE SCRIPTURES ONE READS THAT MAN MUST EARN HIS bread by the sweat of his face. The average man is forced to do some kind of work, even though it may be distasteful to him. In building a home for himself, in spinning and weaving his clothing, and in securing a supply of food, man needs to use his best efforts, and *he must accomplish something*. Effort or force alone is not sufficient. One of man's greatest joys is to experience the feeling that he has done something worth while, and the poet is correct when he writes,

> Count that day lost whose low descending sun,
> Views from thy hand no worthy action done.

In this unit, too, we get a glimpse of James Watt, the inventor of the steam engine, as he experiments with an English dray horse to find out *how rapidly* a horse works. Man, too, has played the part of the guinea pig, and the results of the testing show that seven men can do about the same amount of work in a given time as one horse. For a few seconds, the average man may work at the rate of 550 foot-pounds per second, which is considered one horsepower, but he cannot continue to work at that speed for more than a few seconds.

Civilized man is "energy-minded." Ancient man used his own energy. Then man began to train animals so that he could make use of the energy which they are capable of producing. Watt is said to have become conscious of the energy from steam as he watched the lid of the teakettle bobbing up and down. Then he invented the steam engine, and man uses tremendous quantities of energy from steam, which is really derived from the heat of burning coal or some other fuel. Man harnesses the waterfalls and uses the energy from the so-called "white coal." Windmills for pumping water utilize the kinetic energy from air in motion. Wave motors have been attempted for use of the energy from ocean waves, and some attempts have been made to harness the tides and utilize their limitless energy. In some localities where the sun shines almost every day, sun motors have been used with considerable success in efforts to harness the heat energy of the sun.

# *Work — Power — Energy*

## 1. Work

**191. Work is an accomplishment.** If a man holds a weight of 100 lb. on his shoulder all day long, he is merely exerting force, but in the *scientific sense* he is not doing any work. He does work in lifting the weight to his shoulder. If a man tugs at a 5-ton truck and does not move it, he is not doing any work. *If a force acts upon a body and moves it, then it is said to do work upon the body.* Usually a man is not paid for his *effort,* but for the *effect produced,* or the *work accomplished.* Teachers grade pupils upon the task accomplished and not upon effort. (See Fig. 227.)

**192. How is work measured?** In measuring work, we consider two factors: *force* and *distance.* The amount of work done is equal to the product of *force times distance.* If either the force or the distance is zero, no work is done. Since we have both gravitational and absolute units for measuring force, we must necessarily have two sets of units for measuring work.

1. *Gravitational units.* If one pound of force acts through a distance of one foot, it does one *foot-pound* of work. This unit of work almost defines itself. (See Fig. 229.) A man who weighs 160 lb. does 1600 ft.-lb. of work in climbing a flight of stairs 10 ft. high. He lifts his own weight 10 ft. against the force of gravity. When an object is lifted *vertically,* the amount of work done is always equal to the *weight of the object* times the *vertical height* through which it is lifted. The reason for this is apparent, since one must use a force of 100 lb. to *lift* a weight of 100 lb. The ore unloader of Fig. 228 works rapidly, since it can remove 15 tons of ore per bucketful. Boats containing 13,000 tons of iron ore have been unloaded in 4.5 hours.

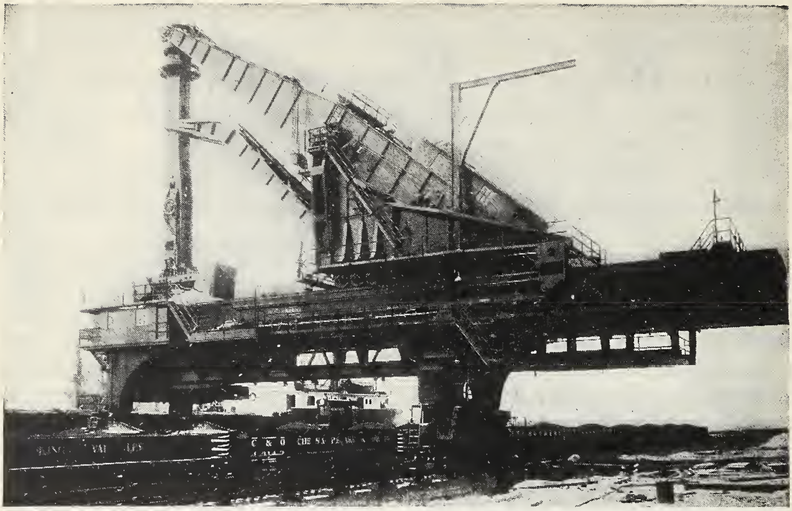
If we *drag* a trunk weighing 150 lb. across a platform 20 ft. long, the amount of work done is less than the product of the weight and the distance. To slide the trunk, all the force that is necessary is to overcome the friction. Suppose that the coefficient of friction is 0.3, then the force needed to keep the trunk moving is 45 lb. (0.3 × 150). The amount of work done is therefore equal to the force (45 lb.) × the distance (20 ft.), or 900 ft.-lb. (See Fig. 230.) To carry the same trunk up a flight of stairs 20 ft. high, one would have to do 3000 ft.-lb. of work. In all cases,

*work = force × distance.*

---

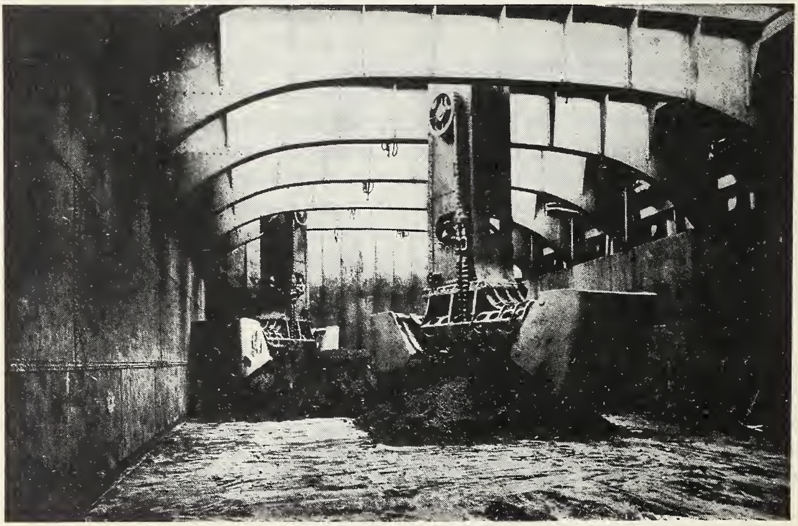
### Vocabulary

FORCE, a push or a pull.
WORK, a force that moves a resisting body does work.
POWER, the rate of doing work.
HORSEPOWER, 550 foot-pounds per second.
ERG, an absolute unit of work.



*Courtesy of the Wellman Engineering Company*

FIG. 227. Such gigantic cranes unload from 10,000 to 12,000 tons of iron ore in four or five hours.



*Courtesy of the Wellman Engineering Company*

FIG. 228. The clam-shell buckets hold from 10 to 15 tons of ore. Compare their size with that of the man in the peephole in the center of the picture. The huge whaleback boats used to carry iron ore are little more than steel shells. They glide up to the ore docks at Duluth or some other port, are filled with 10,000 tons of iron ore in 30 min., and then start their journey southward to the always-hungry blast furnaces.

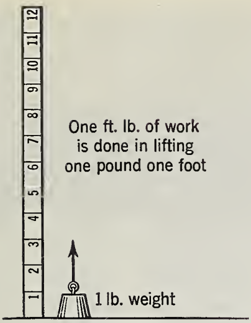

1
2
3
4
5
6
7
8
9
10
11
12
One ft. lb. of work
is done in lifting
one pound one foot
1 lb. weight

FIG. 229. Work done in lifting a weight equals weight times vertical distance.

In the metric system, one may use the *gram-centimeter* as a unit for measuring work, or the *kilogram-meter*. The amount of work done by a force of *one gram* acting through a distance of *one centimeter* is *one gram-centimeter*. The amount of work done by a force of one *kilogram* acting through a distance of *one meter* is a *kilogram-meter*.

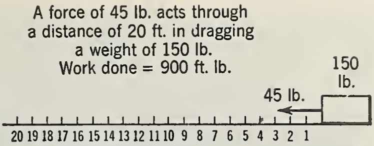

A force of 45 lb. acts through
a distance of 20 ft. in dragging
a weight of 150 lb.
Work done = 900 ft. lb.
150
lb.
45 lb.
20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

FIG. 230. It takes less work to slide a weight a given distance than it does to lift it an equal distance.

★2. *Absolute units.* The absolute unit of work in the English system is the *foot-poundal.* It is the amount of work done by a force of one poundal acting through a distance of one foot. At the latitude of New York City, 32.16 foot-poundals equal one foot-pound. The *erg* is the amount of work done by a force of one dyne in acting through a distance of one centimeter. *The erg is one dyne-centimeter.* There are 980 ergs in one gram-centimeter. The erg is such a tiny unit that the *joule* is often used. This unit, which is named for the English physicist, James Prescott Joule, is equal to 10,000,000 ergs, or $10^7$ ergs.

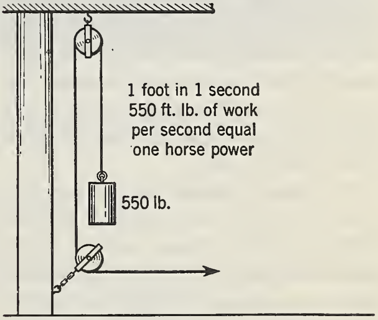
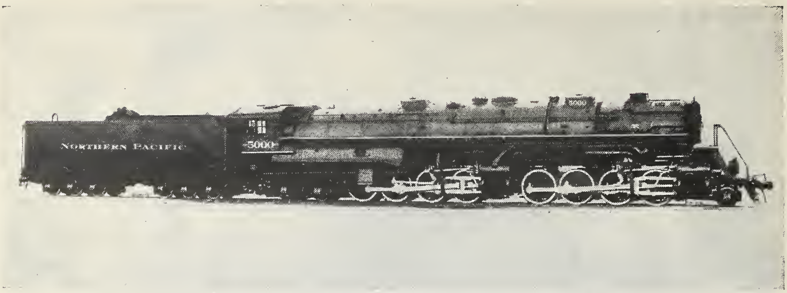

1 foot in 1 second
550 ft. lb. of work
per second equal
one horse power
550 lb.

FIG. 231. How to determine horsepower.

## 2. Power

**193. What is power?** Too often we think of work as anything which makes us tired, but we know that the term "work" cannot be so used in physics. We shall also need to revise our concept of the word "power." We speak of a "powerful" man when we mean that he is strong and capable of exerting great force. In physics we consider the *rate of doing work* when we use the term "power."

When we speak of "force," we are interested in one magnitude only, because *force is independent of both distance and time.* We must consider two things when we speak of "work": force and distance. *Work is independent of time.* A man does the same amount of



*Courtesy of the American Locomotive Company*

FIG. 232. The Yellowstone is the largest steam locomotive in the world. It is 125 ft. long and weighs 1,125,000 lb. It can pull a 4000-ton load up a 1% grade. A mechanical stoker can deliver $22\frac{1}{2}$ tons of coal to the firebox every hour.

work when he climbs a flight of stairs in one minute that he does if he climbs the same flight of stairs in one hour, *but he does not use the same amount of power. Power depends upon three factors: the force exerted, the distance the force moves, and the time required.* We may define *power as the rate of doing work.* (See Fig. 231.)

**194. How is power measured?** In a series of experiments, James Watt, the inventor of the steam engine, found that an English dray horse could continue for a reasonable length of time to work at the rate of 550 *ft.-lb. per sec.* In the English system, the *horsepower* is the unit of power; it is equal to 550 ft.-lb. per sec., or 33,000 ft.-lb. per min. The modern railroad locomotive has a horsepower of from 1000 to 3500. Some automobile engines develop more than 100 horsepower. The airplane used by Hughes was driven by two Wright-Cyclone engines of 1100 H.P. each. The power of the average man is about 78 ft.-lb. per sec. (See Fig. 232.) It is true that almost any adult person can work at the rate of one horsepower for a few seconds. A boy who weighs 110 lb. could probably run up a flight of stairs 20 ft. high in 4 sec. That means that he is developing one horsepower. He might possibly climb a second flight of stairs at the same rate. Do you think that he could continue to run at the same rate up ten flights?

In the metric system the watt and the kilowatt are used as units for measuring power. *The watt is equal to one joule per second. The kilowatt equals 1000 watts.* The horsepower (H.P.) is equal to 746 watts. Hence the horsepower is approximately $\frac{3}{4}$ of a kilowatt. For example, a 15-K.W. engine is about 20 H.P. A 100-H.P. engine can lift a car weighing 4000 lb. to a height of 825 ft. in one minute. (See Fig. 233.) The kilowatt is generally used as a power unit in measuring electricity.

$$\text{H.P.} = \frac{\text{total work in ft.-lb.}}{550 \times \text{time in sec.}}, \quad \text{or,}$$

$$\text{H.P.} = \frac{fs}{550t}.$$

PROBLEM. What horsepower engine is required to hoist 100 tons of coal per hr. from a mine 200 ft. deep?

*Solution.*

$$\text{H.P.} = \frac{\text{total work done (in ft.-lb.)}}{550 \times \text{time in seconds}}. \text{ Then,}$$

$$\text{H.P.} = \frac{100 \times 2000 \times 200}{550 \times 60 \times 60};$$ the answer is 20.2 H.P.

FIG. 233. James Watt (1736–1819) is generally considered the inventor of the steam engine. He improved the old Newcomen engine by adding valves to make it double acting. He built the first compound engine. His inventions include the governor, the water and steam gauges, and the steam hammer. He started experimenting when a mere boy.

## PROBLEMS

### GROUP A

1. How much work would you do in climbing a flight of stairs 20 ft. high? What is your horsepower, if you run up the stairs in 10 seconds? Suppose the time is 10 seconds or less; does the result show that $\frac{1}{7}$ H.P. is too low an estimate for the average man power?

2. If a horse pulls with a force of 240 lb. to keep an 800-lb. wagon moving, how much work does he do in pulling the wagon $\frac{1}{4}$ mile? If he moves at the rate of 2 mi. per hr., what H.P. does he use?

3. If each of the citizens of a city of 400,000 inhabitants uses 5 gallons of water (40 lb.) daily, what H.P. engines must be used if the height to which the water must be pumped is 100 feet?

4. The elevator in the Empire State Building makes the ascent to the 80th floor in 50 seconds. If the height is 989 ft., what H.P. is used in lifting a 200-lb. man to this floor?

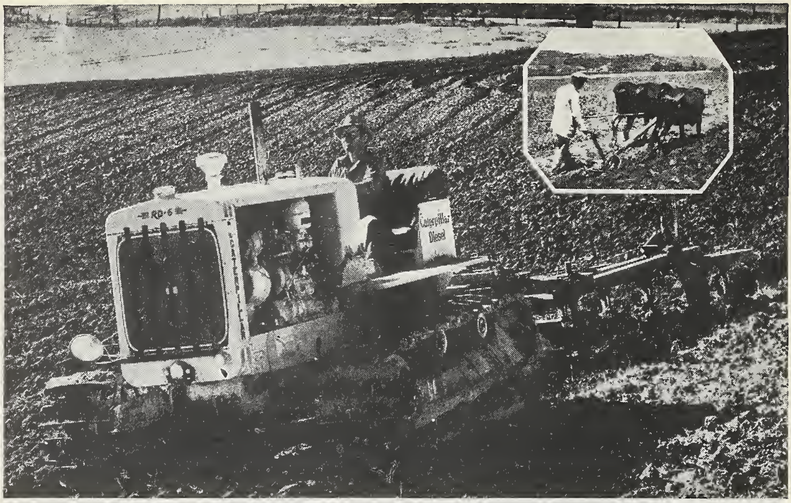
5. What H.P. would you use in climbing a mountain 2500 ft. high in 30 minutes? Since you could probably walk 4 times that far in 30 minutes, give a reason why mountain climbing is so slow.

6. How many tons of ore can be lifted from a mine 900 ft. deep by an 80-horsepower engine working 24 hours?

### GROUP B

7. A block of wood 4 ft. 6 in. long is 1 ft. thick. Its weight is 400 lb. If the block lies on its side, how much work does a man do in standing the block on end?

8. If the coefficient of friction is 0.15, what force is needed to pull a sled that weighs 300 lb.? How much work does a man do in pulling the sled one mile? If he could cover the mile in 15 min., what would be his horsepower? Do you think he could do it?



Courtesy of the Kimberly-Clark Corporation

FIG. 234. The farm tractor is extensively used on the farm for pulling farm machinery. It travels faster than the oxen, pulls a heavier load, and it does not get tired.

9. A locomotive pulls a train at the rate of 60 mi. per hr. as it develops 500 H.P. What effort must it use?

10. A man who weighs 180 lb. carries 100 lb. of sugar to a height of 30 ft. How much work does he do? What per cent of the work he does would you consider useful work? At the rate of 78 ft.-lb. per sec., how long should he take?

11. Suppose that man power is about 4600 ft.-lb. per minute. How many trips per hour should a 150-lb. man make up a ladder 20 ft. high, if he carries 50 lb. of brick each time? (Allow one-third of the time for the down trips).

12. An automobile weighing 3600 lb. climbs a mountain 6000 ft. high in 20 min. What horsepower is needed?

## 3. Energy

**195. What is energy?** We have already defined *energy as the capacity for doing work.* Flowing water has energy because the pull of gravity has given it velocity. Wind is a similar example. Waves and tides, too, have energy. An inanimate body has energy, provided work has been done in lifting it to an elevated position or in imparting to it velocity. In the first case it has energy of position. In the second case it has energy due to its momentum.

The heat energy that we derive from our foods enables us to do work. Heat may convert water into steam. Because steam has expansive force, it is able to exert pressure and do work. Physics also deals with energy which may be obtained from electricity or light. (See Fig. 234.)

**196. What kinds of energy are there?** Energy is of two kinds, *kinetic* and *potential. Kinetic energy is energy of motion;* a body has kinetic energy because of its velocity. A moving cannon ball, strong winds, falling and running water are all examples of kinetic energy. *Potential energy is stored energy, or energy of position.* A rock resting on a precipice has potential energy; if it falls over the edge, its energy becomes kinetic. A coiled spring has potential energy. Work was done in winding the spring; as it unwinds, its energy becomes kinetic. Gasoline has potential energy. When a mixture of gasoline vapor and air explodes, it is capable of doing work. If we pull to one side a heavy pendulum bob, we are storing up *potential* energy as we lift the bob against gravity. As the bob swings downward and forward, the potential energy becomes *kinetic.* The kinetic energy released is sufficient to carry the bob upward again on the opposite side, thus storing up more potential energy. It is possible to change kinetic energy to potential, and vice versa.

**★197. How is energy measured?** Since energy is the capacity for doing work, then the work units can also be used to measure energy. For example, we do 120 ft.-lb. of work in lifting 40 lb. to a table 3 ft. high. The weight in its elevated position has acquired 120 ft.-lb. of potential energy. In falling a distance of 3 ft., this stored energy could do 120 ft.-lb. of work. (See Fig. 235.)

Potential energy equals $mh$, or mass times height. If the mass is expressed in grams and the height or distance in centimeters, then the potential energy will be expressed in gram-centimeters. If the mass is expressed in pounds and the distance in feet, the potential energy will be expressed in foot-pounds. To find potential energy in ergs or foot-poundals, we use the formula: P.E. (in ergs or foot-poundals) = $mgh$. Of course, $g$ is the acceleration due to gravity, 980 cm. per sec. per sec., or 32.16 ft. per sec. per sec.

If the velocity of the body is given, its kinetic energy may be found by the use of the following formula:

$$\text{K.E. (in ergs)} = \tfrac{1}{2}\,mv^2.$$

The above formula is derived from the formulas $mgh$ and $v = \sqrt{2gS}$. $S$ and $h$ both represent distance. From $v = \sqrt{2gS}$, we get

$$S = \frac{v^2}{2g}.$$

Substituting,

$$\text{K.E.} = mg \times \frac{v^2}{2g}.$$

Or, K.E. $\frac{1}{2}\,mv^2$.

PROBLEM. A bullet having a mass of 50 gm. moves with a velocity of 1000 meters per second. Find its kinetic energy in ergs and in gram-centimeters. In kilogram-meters.

*Solution.* Substituting in the formula, K.E. = $\frac{1}{2}mv^2$, we have the following: K.E. $= 25 \times (100{,}000)^2$, or 250,000,000,000 ergs. Dividing the number of ergs by 980, we have 25,510,201 gm.-cm. There are 100,000 gm.-cm. in 1 kgm.-m. Hence 25,510,201 gm.-cm. = 255 kgm.-m.

In the English system.

K.E. (in foot-poundals) = $\frac{1}{2}mv^2$, when $m$ is expressed in pounds and $v$

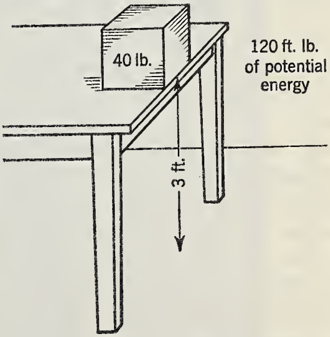
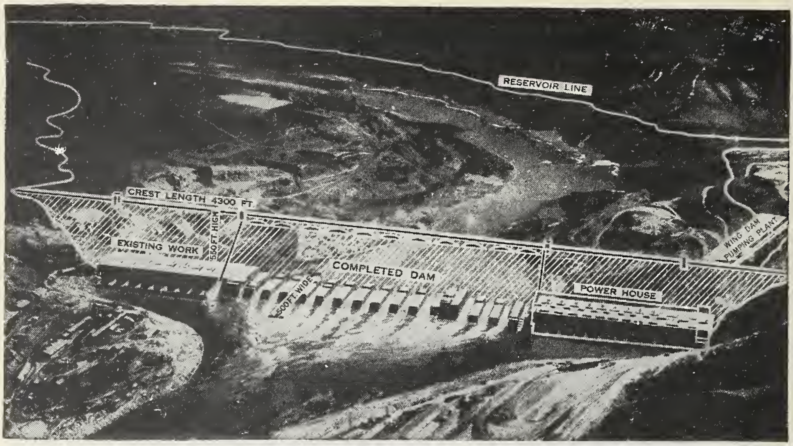


FIG. 235. Potential energy equals weight times vertical height. As the weight falls, its energy becomes kinetic.



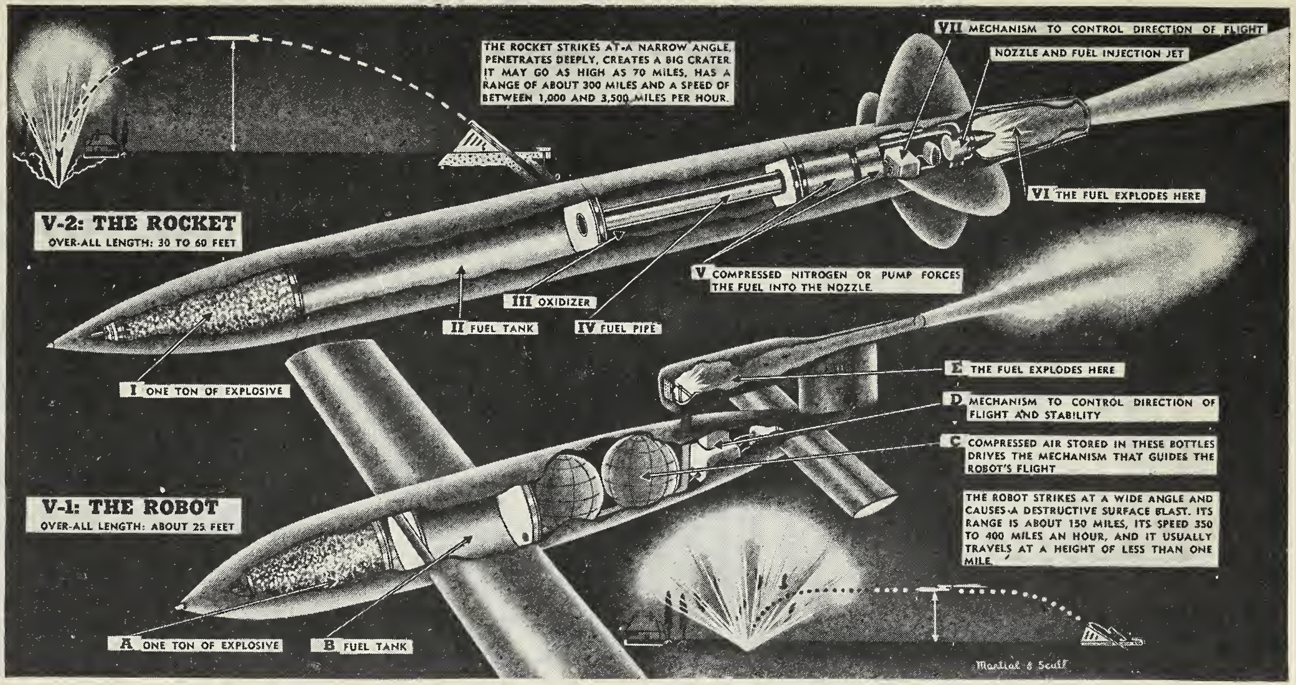
*Courtesy of the Department of Interior*

FIG. 236. The Grand Coulee Dam is the biggest thing on earth. The crest length is 4300 ft., and the height is 553 ft. The contract calls for 6,000,000 cu. yd. of concrete.

in feet per second. Dividing by 32.16 gives the K.E. in foot-pounds.

**198. What is meant by conservation of energy?** Like matter itself, energy can neither be created nor destroyed. There is the same amount of energy in the universe today that there was yesterday, and the amount will be unchanged tomorrow. These facts show why the *output* of a machine can never exceed the *input*. A perpetual-motion machine is utterly impossible. Even if friction and the weight of the parts could be eliminated, the machine could never create energy; it would never have any more energy than was put into it.

**199. Energy can be transformed.** Although energy cannot be created, it can be transformed from one kind into another. We have already learned that it is possible to transform kinetic energy into potential energy, and vice versa. Heat energy can be transformed into mechanical energy, mechanical into electrical, and electrical into mechanical, heat, or light energy. Let us use just one concrete example. Heat from the sun evaporates water; some of this vapor, which is carried by winds, may fall as rain into Lake Erie. Here its potential energy is transformed into kinetic as the water flows down Niagara River to the Falls. This transformation continues as it passes through the turbine pits and turns the large wheels at the bottom, thus producing mechanical energy. The turbines turn alternators which generate electricity. This electrical energy is transmitted to various places, where it is utilized for lighting, heating, or in the mechanical work of turning motors. In these cases heat energy is set free, either in doing useful work or in overcoming friction. This heat may evaporate more water to begin anew the energy transformations. During all these transformations the total amount of energy is unchanged. The fact that energy may be transformed or transferred, but cannot be destroyed, is known as the *law of the conservation of energy.*


THE ROCKET STRIKES AT A NARROW ANGLE, PENETRATES DEEPLY, CREATES A BIG CRATER. IT MAY GO AS HIGH AS 70 MILES, HAS A RANGE OF ABOUT 300 MILES AND A SPEED OF BETWEEN 1,000 AND 3,500 MILES PER HOUR.
VII MECHANISM TO CONTROL DIRECTION OF FLIGHT
NOZZLE AND FUEL INJECTION JET
V-2: THE ROCKET
OVER-ALL LENGTH: 30 TO 60 FEET
VI THE FUEL EXPLODES HERE
V COMPRESSED NITROGEN OR PUMP FORCES THE FUEL INTO THE NOZZLE.
III OXIDIZER
II FUEL TANK
IV FUEL PIPE
I ONE TON OF EXPLOSIVE
E THE FUEL EXPLODES HERE
D MECHANISM TO CONTROL DIRECTION OF FLIGHT AND STABILITY
C COMPRESSED AIR STORED IN THESE BOTTLES DRIVES THE MECHANISM THAT GUIDES THE ROBOT'S FLIGHT
V-1: THE ROBOT
OVER-ALL LENGTH: ABOUT 25 FEET
THE ROBOT STRIKES AT A WIDE ANGLE AND CAUSES A DESTRUCTIVE SURFACE BLAST. ITS RANGE IS ABOUT 150 MILES, ITS SPEED 350 TO 400 MILES AN HOUR, AND IT USUALLY TRAVELS AT A HEIGHT OF LESS THAN ONE MILE.
A ONE TON OF EXPLOSIVE
B FUEL TANK
Martial & Scull

*Courtesy of Martial and Scull, Industrial Designers, with permission of the* New York Times

This is a schematic diagram worked out by engineers and showing what they believe to be the design and construction of the robot bomb, $V_1$, and the rocket bomb, $V_2$.

## Summary

When a force acts upon a body and produces motion, work is done upon that body. The gm.-cm., kgm.-m., and ft.-lb. are gravitational units of work. The erg, the joule, and the foot-poundal are absolute units of work. One foot-pound equals 32.16 foot-poundals. One gram-centimeter equals 980 ergs.

Power is the rate of doing work. The horsepower, watt, and kilowatt are the units of power. The horsepower equals 550 ft.-lb. per second.

Energy is the capacity for doing work. The units of work are used to measure energy. Energy can neither be created nor destroyed. It may be transformed in practically any manner.

In dealing with force, we consider magnitude only; with work, we consider both magnitude and distance; with power, we consider magnitude, distance, and time.

*How many of the following terms can you define or explain?* (*The prize is earned by the dust of labor.*)

Units of work
Erg
Joule
Kilogram-meter

Units of power
Horsepower
Watt
Kilowatt

Kinetic energy
Potential energy
Conservation of energy
Transformations of energy

## PROBLEMS

### Group A

1. Find the potential energy of 1 cu. ft. of water at the top of Niagara Falls. (Height equals 167 ft.)

2. A waterfall is 140 ft. high. If 1000 cu. ft. of water flow over it per second, what horsepower can it develop?

3. An automobile weighing 3000 lb. climbs at the rate of 30 mi. per hr., a hill that rises 8 ft. in 44 ft. of its length. What is the minimum horsepower developed by the engine?

4. A pile driver weighs 1000 lb. In falling 4 ft. how far will it drive a pile if the earth resistance is 6000 lb.?

5. An automobile weighs 3500 lb. and is moving with a velocity of 45 miles per hour. What is its momentum? Is its kinetic energy the same?

### Group B

6. A projectile weighing 1000 lb. moves with a velocity of 2500 ft. per sec. Find its kinetic energy in foot-poundals; in foot-pounds; in foot-tons.

7. If all the kinetic energy of Problem 6 were transformed into work, to what height could the projectile be lifted? (Divide kinetic energy in ft.-lb. by the weight of the projectile.)

8. Using the formula, $v = \sqrt{2gS}$, find out how high a body projected upward with a velocity of 2500 ft. per sec. would rise. Compare the result you obtain with the answer to Problem 7.

9. Calculate the kinetic energy of the automobile of Problem 5, first in foot-poundals and then in foot-pounds.

10. How many cubic feet of water per second must pass over a waterfall 220 ft. high in order to develop 120,000 horsepower?

11. An engine hoists 200 metric tons of coal from a mine 160 meters deep in 10 hours. If it works at 100% efficiency, what is the rating of the engine in kilowatts?

12. A rifle weighs 10 lb. It fires a bullet weighing 3 oz. at a velocity of 2000 ft. per sec. What is the momentum of the rifle in recoil? What is the kinetic energy of the bullet? Of the rifle?

# Unit Five

# *Machines*

## Preview

FORMERLY, THE PATENT OFFICE IN WASHINGTON REquired every inventor who was applying for a patent to submit a small working model of the machine or device which he had invented. The requirement was discontinued when the hundreds of thousands of models began to take up so much room that it was difficult to find a place to house them. It has been said, "Of the making of many books there is no end." The same may be said of the machines which are the product of man's ingenuity. Because that is true, one might suspect that the study of machines in physics would offer many difficulties. It would be most difficult, too, if man had not learned how to classify things. Many of the machines that we see appear complicated, and some of them are. If we proceed to analyze them, we find that they are all built by using combinations of the six simple machines. In this unit we shall study the six simple machines: the lever, the pulley, the wheel and axle, the inclined plane, the wedge, and the screw. Then we can the more easily understand how some complicated machines are made by compounding simple machines.

In this machine age, man invents machines to do his work. Possibly he designs a machine to multiply his feeble efforts. Other machines which he has devised make it possible for him to travel as fast as if he had seven-league boots.

With all his creative efforts, man cannot get more energy from a machine than he puts into the machine. No machine creates energy. The principle of the law of the conservation of energy is so firmly believed that applications for patents on perpetual-motion machines are thrown into the wastebasket as impractical when they reach the Patent Office in Washington.

World War II has justly been called the War of Machines. In the water we might find battleships, some of them of 45,000 tons displacement, heavy cruisers, light cruisers, destroyers, submarine chasers, submarines, PT boats or motor torpedo boats, aircraft carriers, transport vessels, amphibious landing boats, and amphibious planes. On land one might meet mountain-goat jeeps, motor trucks, bulldozers, light and heavy artillery, rifles, machine guns, bazookas, and both light and heavy tanks in motorized units which can travel with amazing speed. The air might be filled with sausage balloons, parachutes, fast scout planes, speedy fighter planes, transport planes, huge bombers, riderless robots or "doodlebugs," incendiary bombs and demolition bombs. The aquatic, land, and air machines all combine to make modern war the inferno that it is today. Scientists have at times been criticized for inventing destructive machines, but it hardly seems just to blame either the machines or the scientists who invented them because certain warmongers divert such machines from their legitimate uses and apply them for warlike purposes.

# Machines

## 1. Definitions — Principles

**200. Why do men invent machines?** Without the aid of machines, man could hardly have been able to combat the tremendous forces of nature or conquer the ferocious beasts of our forests. Perhaps in many cases necessity was the mother of invention. The Greek philosopher, Archimedes, said that he could lift the earth if he had a long enough lever and some place to put the fulcrum. Man uses some machines to *transform energy.* The dynamo, for example, changes mechanical energy into electrical energy. The steam engine transforms heat energy into mechanical energy. The energy of flowing water is transformed into electrical energy by hydro-electric machines. Man often uses machines to *transfer energy* from one place to another.

A nail that cannot be pulled with the fingers may be drawn with a claw hammer used as a lever. By means of a jack, the axle of an automobile may be lifted so that the wheel or tire can be removed. Two men wish to hoist a piano to the second floor of a house. If either one were strong enough, he might carry it upstairs. Instead they arrange a system of pulleys called a "block and tackle" by means of which the piano can be hoisted with less force. In all these cases, a machine has been used to multiply man's rather feeble force. *One important use of machines is to multiply force or effort.* Since in every case the time has been increased, *we gain effort at the sacrifice of time or speed.*

A bicycle is a machine used *to gain speed.* In this case we gain speed by increasing our effort. If we try to ride a bicycle uphill we become aware of the fact that we are gaining speed by increased effort. It is impossible to gain both force and speed at the same time. The bones of the forearm are levers used to gain speed. We conclude that *machines are used by man to multiply speed.*

To put up a flag on a tall pole, one

### Vocabulary

MACHINE, a device to transfer or transform energy.

MECHANICAL ADVANTAGE, the advantage of force or speed gained by the use of a machine.

EFFICIENCY, the ratio of the useful work accomplished to the total work expended.

PENSTOCK, a tube or conduit for conducting water to a turbine.

CAM, a projection on one side of a rotating wheel designed to impart motion to a roller in contact with the edge of the wheel.

RECIPROCATING, backward and forward, or to and fro, as distinguished from rotary.

GRADE, the ratio of the height of an incline to its length.

MICROMETER, a device used to measure objects with great accuracy.

*could* climb the pole and carry the flag with him. It is much more convenient, however, to have a pulley at the top of the pole, and a rope twice the length of the pole. Then one can stand on the ground and pull the flag up by means of the rope. He must pull downward with a force of 1 lb. for every pound the flag weighs. Hence this single pulley as a machine *does not multiply force.* He must shorten the rope one foot for every foot the flag is raised; hence the pulley *does not multiply speed.* Such a machine is used only as a convenience *to change direction.* The pulley clothes line, the pulley for lifting awnings, and many similar devices, are other examples of machines used to change direction. The farmer who wishes to use a team of horses to lift hay up into a mow would have difficulty in getting his horses up into the mow to pull upward. He would find it difficult to hitch his horses to a rope so that they could pull downward. By the use of two or three fixed pulleys, fastened to the rafters and along the post by the side of the barn door, the horses can pull horizontally while the hay moves upward.

**201. What are the simple machines?** Six simple machines are usually discussed in physics: the *lever;* the *pulley;* the *wheel and axle;* the *inclined plane;* the *screw;* and the *wedge.* Other machines are either modifications of one of these simple machines or combinations of two or more of them. It is also quite easy to show that the pulley and the wheel and axle are really levers, and that the wedge and the screw are inclined planes.

**202. What is mechanical advantage?** In Section 42 we learned that a machine has a mechanical advantage of 5, if by its use 1 lb. of effort can counterbalance 5 lb. of resistance. In all the simple machines we shall use the term *mechanical advantage* frequently. There are two ways in which this mechanical advantage can be found. 1. By the use of a spring balance, the *acting force, E,* can be measured and also the *resisting force, R.* Then the mechanical advantage equals $\frac{R}{E}$, providing friction is neglected. 2. With a ruler we may measure the *distance the effort* moves, *De,* and also the *distance the resistance moves, Dr.* In this case, the mechanical advantage equals $\frac{De}{Dr}$. In dealing with mechanical advantage we always assume that the parts of the machine have no weight and that there is no friction. Of course, such an assumption is theoretical; it tells us what a machine *should* do under *ideal* conditions.

**203. What is the general law of machines?** In the preceding section, we had two statements for mechanical advantage. Both are equal to each other. Then,

$$\frac{R}{E} = \frac{De}{Dr}. \quad \text{Or, } E \times De = R \times Dr.$$

In all frictionless machines, *the effort multiplied by the distance the effort moves equals the resistance multiplied by the distance the resistance moves.* This statement is known as the *Law of Machines.*

The effort times the distance it moves equals the *work* put into the machine, or *input.* The resistance times the distance it moves equals the work accomplished by the machine, or its *output.* If we *neglect friction and weight of parts, input equals output.*

**204. What is efficiency?** When a man rides a bicycle up a hill, he must lift his own weight and also that of the bicycle the vertical height of the hill.

Lifting the bicycle is really *useless work*. No machine ever runs without some friction. Overcoming friction wastes work. Hence, input is always greater than output. In practice, we are more interested in what a machine *actually does* than in what it *should do theoretically*. We are concerned with the useful work that is accomplished. *The efficiency of a machine is the ratio of the useful work accomplished to the total work expended*. Or,

$$\text{Efficiency} = \frac{\text{useful work}}{\text{total work}}.$$

When efficiency is considered, *input equals useful work plus friction*. Efficiency is usually expressed in per cent. If a pupil solves 8 problems out of 10 correctly, his efficiency is 80%. If a machine has a total input of 1000 ft.-lb., and its useful output is only 800 ft.-lb., the machine is working at an efficiency of 80%.

Suppose that an effort of 40 lb. moves 20 ft. along an inclined plane and in so doing lifts a weight of 180 lb. to a height of 4 ft. The *useful* work done equals 4 × 180, or 720 ft.-lb. The *total* work equals 40 × 20, or 800 ft.-lb. Then the efficiency equals $\frac{720}{800}$; dividing, we get a quotient of 0.90, or 90%.

If we have a machine which has a mechanical advantage of 5, a force of 20 lb. should support a weight of 100 lb. If actual experiment shows that it takes 25 lb. to support 100 lb., then the efficiency of the machine is $\frac{20}{25}$, or 80%. The additional 5 lb. of force required to counterpoise the weight of the machine itself represents wasted effort. In some machines the work wasted may exceed the useful work.

## 2. The Lever

**205. The lever is a machine.** When a man rows a boat, he uses the oars as levers. We see a man using a crowbar to lift a heavy load. He is using the same kind of a lever Archimedes would have used to lift the earth. The can opener, the broom, and the shovel are levers used around the house. The lever consists of a rigid bar free to turn about a fixed point called the *fulcrum*. The fulcrum is essentially the center of moments, and the effort and resistance act upon the arms of the lever as they tend to produce rotation in opposite directions. In using the lever, we make use of the principle of moments.

**206. How can we calculate the mechanical advantage of the lever?** In Fig. 237 we shall use the letter $F$ to represent the fulcrum of the lever $ER$. At $E$ the effort acts upon the arm $EF$ as it tends to produce *counter-clockwise* rotation. The resistance $R$ acts upon the arm $RF$ as it tends to produce *clockwise* rotation. While the effort moves from the point $E$ to $E'$, the resistance will move from $R$ to $R'$. But the distance $EE':RR' = EF:RF$. Hence it follows that the distances moved by the effort and resistance are propor-

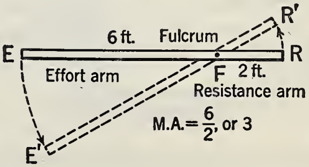


FIG. 237. Mechanical advantage of the lever

tional to the lengths of the arms upon which they act. In all frictionless machines,

$$\text{M.A.} = \frac{De}{Dr}.$$

In all kinds of levers,

$$\text{M.A.} = \frac{EF}{RF},$$

or the length of the effort arm divided by the length of the resistance arm. If *EF* is 6 ft. long, and *RF* is only 2 ft. long, then the mechanical advantage is 3.

**207. What are the classes of levers?** 1. With a lever it is possible to have the effort act at or near one end. The resistance is placed at the opposite end of the lever, and the fulcrum is between the two. (See Fig. 238.) Such a lever is known as a *first-class* lever. Such a lever may be used to gain speed, to gain force, or to change direction. The beam balance, Fig. 239, is a common example of a lever of this class. If such a balance is well constructed, the two arms are of equal length and the light, rigid beam rests upon a very hard, knife-edged fulcrum. Accurate weighings can be made with such a balance. If *EF* exceeds *RF* in length, we have a mechanical *advantage of force*. The pump handle of Fig. 101 is a common example. The mechanical advantage is more than *one*, because the effort arm exceeds in length the resistance arm. The tinner's shears of Fig. 240 furnish another example. Sometimes a first-class lever is used to gain speed. Then the effort arm is shorter than the resistance arm. The force advantage is a fraction in such cases. Paper shears, or those used by a tailor, are examples. (See Fig. 241.)

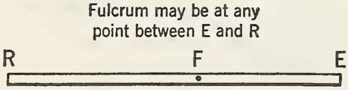


Fig. 238. The first-class lever.

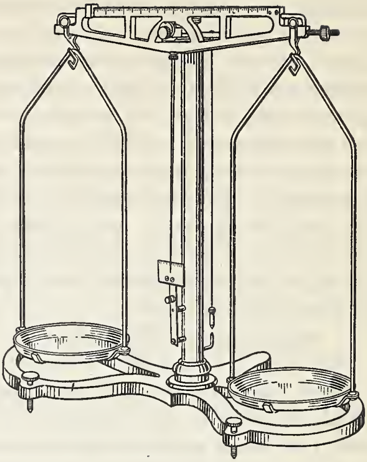


Fig. 239. The beam balance is a first-class lever.

2. Sometimes the effort is applied at one end of a lever and the fulcrum is at the other end. The resistance is placed between the effort and the fulcrum. (See Fig. 242.) Such a lever is known as a *second-class* lever. In a wheelbarrow, the axle of the wheel is the fulcrum. The effort is applied at the ends of the handles, and the load or resistance is between the two. (See Fig. 243.) Since the effort arm of a second-class lever is the *whole* lever, and the resistance arm is only a *part* of the lever, *EF* is always greater than *RF*. The mechanical advantage of such a lever is always *more than one*. The nutcracker and the baggage-truck are other examples of this class of lever.

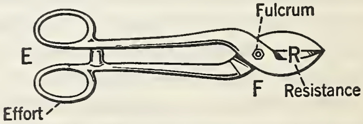


Fig. 240. Tinner's shears have long handles and short blades.

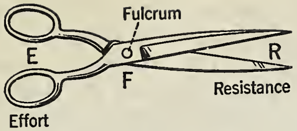


FIG. 241. Paper shears have short handles and long blades.

If two boys carry a load on a pole between them, we may consider the pole a second-class lever and one of the boys the fulcrum. Then it is easy to find the force which the second boy must use to lift the load.

3. When we lift a weight on the hand, we use the forearm as a *third-class* lever. The fulcrum is at the elbow. The resistance is at the other end of the lever, on the hand, and the tendons attached to the bones of the forearm act as the effort. (See Fig. 244.) This lever differs from the second-class lever in one way only. The positions of the effort and resistance have been interchanged. (See Fig. 245.) The resistance arm is longer than the effort arm; hence the resistance must move faster than the effort. Such a lever is used to gain speed. Of course we gain speed by sacrificing force. A fork, a shovel, or a broom may be used as a third-class lever; sometimes they are used as first-class levers. We find it very hard to open a door by pushing near the hinge. The resistance is *concentrated at the center of gravity* of the door, and we have been using a third-class lever. The door opens much more easily when we push near the other edge of the door, using a second-class lever, but the hand must move farther.

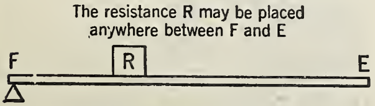


FIG. 242. The second-class lever.

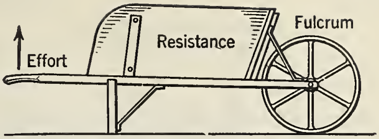


FIG. 243. The wheelbarrow is a second-class lever.

★208. **How is a lever affected by its own weight?** In the preceding section, we neglected the weight of the lever. In practice, the weight of the lever must be considered. We must keep in mind that the lever *acts as if all its weight were concentrated at its center of gravity.*

In Fig. 246, the uniform bar $AB$ is 12 ft. long; its weight is 60 lb. At $B$, 2 ft. from the fulcrum, there is a resistance of 300 lb. We wish to find what effort at $A$ is needed to produce equilibrium. The resistance moment equals $2 \times 300$, or 600. It acts clockwise. The effort moment equals $10 \times x$, or $10x$; its direction is counter-clockwise. But the weight of the lever, 60 lb., acting at its center of gravity, 4 ft. from the fulcrum, is really producing a counter-clockwise moment and helping the effort. The sum of the two counter-clockwise moments is $10x + (4 \times 60)$. This sum equals the clockwise moment, 600. From the equation, $10x + 240 = 600$, we find that $x = 36$ lb., the effort needed at $A$.

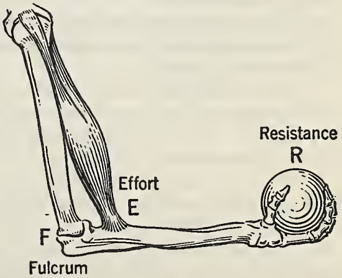


FIG. 244. The forearm is a lever that is much used to gain speed.

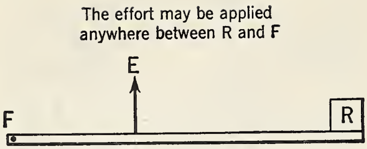

The effort may be applied anywhere between R and F
E
F
R

FIG. 245. The third-class lever.

In Fig. 247 the weight of the lever hinders the effort, since it acts in a counter-clockwise direction, the same as the resistance. The lever $EF$ has the fulcrum at the end $F$, and the effort is applied at the other end $E$. The lever, which is 12 ft. long, weighs 60 lb. A resistance of 300 lb. is applied at $R$, 2 ft. from the fulcrum. We wish to find the effort needed at $E$ to secure equilibrium. The resistance moment, 2 × 300, or 600, and the weight moment, 6 × 60, or 360, are both acting in a counter-clockwise direction. Their sum is 960. The effort moment, $12 \times x$, or $12x$, acts clockwise. Therefore $12x = 960$, and $x = 80$ lb., the effort needed at $E$. *A lever acts as if all its weight were concentrated at its center of gravity; its weight-moment equals its weight multiplied by the distance from the center of gravity to the fulcrum.*

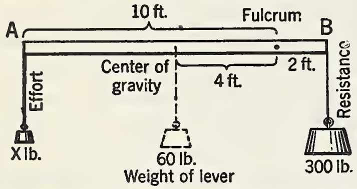

10 ft.
Fulcrum
A
B
Center of gravity
4 ft.
2 ft.
Effort
Resistance
X lb.
60 lb.
Weight of lever
300 lb.

FIG. 246. The weight of this lever acts as a counter-clockwise moment and aids the effort.

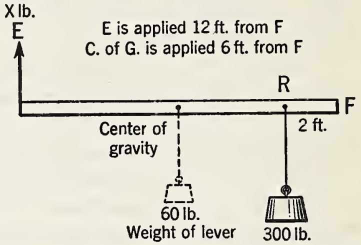

X lb.
E
E is applied 12 ft. from F
C. of G. is applied 6 ft. from F
R
F
2 ft.
Center of gravity
60 lb.
Weight of lever
300 lb.

FIG. 247. The weight of this lever hinders the effort.

## QUESTIONS

1. Determine the position of the effort, fulcrum, and resistance in each of the following: a claw hammer used for pulling nails, Fig. 248; a pair of sugar tongs; a nutcracker; the oar of a rowboat; the lower jaw.

2. Where should the resistance be placed to secure a high mechanical advantage with a second-class lever?

3. Where must the effort be placed with a third-class lever to secure a high mechanical advantage of speed?

4. Draw diagrams to show how you would arrange at least two levers so that the weight of the lever really helps the effort counterbalance the resistance.

5. Draw a diagram to show a case where the weight of the lever is really a hindrance to the effort.

6. Why is it impossible to have a machine with an efficiency of more than 100%?

7. In a lever where the weight of the lever serves to aid the effort it may seem as if the efficiency is more than 100%. Where does the discrepancy occur?

8. Which of the two methods of finding the mechanical advantage of a machine is the more accurate? Explain why.

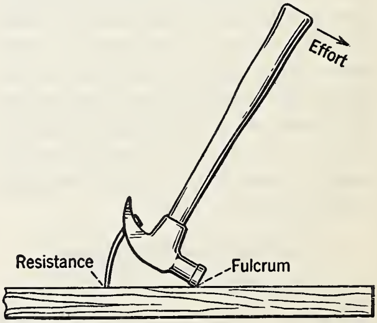

Effort
Resistance
Fulcrum

FIG. 248. The hammer in this figure is a bent lever of the first class.

## PROBLEMS

### Group A

1. A man uses a plank 15 ft. long as a lever of the second class. Neglecting the weight of the plank, what effort is needed to lift a resistance of 500 lb. placed 3 ft. from the fulcrum?

2. What effort will be needed to lift the load of Problem 1 if the plank is used as a first-class lever? (Load 3 ft. from fulcrum.)

3. A boy weighing 90 lb. sits on one end of a seesaw, 6 ft. from the fulcrum. A second boy is 9 ft. from the fulcrum. What is his weight, if the seesaw is counterbalanced?

4. A bar 8 ft. long is to be used as a lever of the second class. How far from the fulcrum must the resistance be placed if a force of 80 lb. is to balance 600 lb.?

5. What mechanical advantage is needed for 60 lb. to counterbalance 240 lb.? Make a diagram of a first-class lever 10 ft. long with the effort, fulcrum, and resistance properly arranged to give such an advantage.

6. A man has a fishing pole 15 ft. long. One hand at the end of the pole acts as the fulcrum, and the other hand, 1 ft. from the end, as the effort. What effort is needed to pull from the water a 5-lb. fish?

### Group B

7. A plank 18 ft. long lies on a flat roof with one end extending 2 ft. beyond the edge of the roof. The plank weighs 140 lb. How heavy a weight can be hung from the end of the plank without pulling the plank off the roof? What is the safety factor if a man who weighs 160 lb. stands on the end of the plank?

8. A uniform bar 8 ft. long weighs 24 lb. What weight must be applied to one end of the bar to make it balance on a fulcrum placed just 1 ft. from that end?

9. The weight of a uniform bar 30 ft. long is 600 lb. The fulcrum is at *F*, 5 ft. from the end to which a weight of 2000 lb. is attached. What effort will be needed at the other end to counterbalance the combination?

10. A meter stick loaded at one end balances on a fulcrum placed 20 cm. from the loaded end. When a weight of 500 gm. is attached to the unloaded end, the combination balances on a fulcrum placed 35 cm. from the 500-gm. weight. Find the weight of the loaded meter stick.

11. A pole 50 ft. long has its center of gravity 15 ft. from one end. A weight of 2000 lb. is suspended from this end. If the pole weighs 1000 lb., what effort at the other end will balance the pole on a fulcrum placed midway between the ends?

12. A uniform bar, 24 ft. long, weighs 1000 lb. The fulcrum is 6 ft. from the end *A*, from which a weight of 500 lb. is suspended. What effort at the other end is needed to produce equilibrium?

13. A pole *AB* is 40 ft. long. It weighs 400 lb., and its center of gravity is 15 ft. from the end *A*, which is 10 ft. from the fulcrum. A weight of 1500 lb. is attached at *A*, and a weight of 200 lb. is suspended at a point 5 ft. from *B*. Where must a weight of 400 lb. be applied to produce equilibrium? Where would you place a weight of 600 lb.?

## 3. The Pulley

**209. What is a pulley?** The simple machine known as the *pulley* consists of a wheel, usually grooved, so mounted in a frame or block that it may turn readily upon a fixed axis. The frame may be made of metal or of wood. Two or more wheels may be mounted in the same frame, either on the same axis, as in Fig. 249, or on different axes, as in Fig. 250. When two or more wheels are mounted in the same block, the pulley is said to have two or more *sheaves*. For the sake of clearness, we shall use pulleys of the type shown in Fig. 250 in diagrams, although those of the type shown in Fig. 249 are more often used in actual practice.

**210. Where are pulleys used?** The cords that support our windows pass over fixed pulleys in the window frame. We use a pulley to raise flags, awnings, and some window shades. Men use a combination of ropes and pulleys for putting hay into a mow. The painter uses pulleys to raise or lower the ladders he uses as a platform. An elevator cable passes over a pulley to a drum, upon which the cable is wound as the elevator is lifted. The moving van is equipped with a block and tackle, which is a system of pulleys, for use in lifting heavy pieces of furniture to the upper floors of a dwelling.

**211. For what is a single fixed pulley used?** A single fixed pulley is really a lever of the first class. The arms *EF* and *RF*, Fig. 251, are equal; hence the mechanical advantage is one. When 1 lb. pulls downward at *A* through a distance of 1 ft., a resistance of 1 lb. at *B* is raised 1 ft. A single fixed pulley gains neither force nor speed; its purpose is to change the direction in which a force is applied.

**212. For what is a single movable pulley used?** The single movable pulley is really a lever of the second class. In Fig. 252, the effort *E* acts upon the arm *EF*, which is the diameter of the pulley. The resistance *R* acts upon the arm *RF*, which is the radius of the pulley. Since the diameter is twice the radius, the mechanical advantage of the single movable pulley is two. When the effort at *A* moves 2 ft., the resistance at *B* is lifted 1 ft. If we fasten both ends of the cord, it is evident that each point of support bears one-half the weight.

**213. How are pulleys combined?** It is possible to have many different combinations of fixed and movable pulleys. We shall consider two cases, in both of which the cord or rope is continuous. Of course the effort is applied to one end of the cord, and the

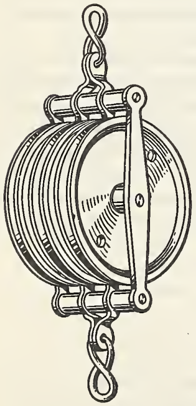


Fig. 249. Pulley, with three sheaves, all on the same axle. A common type.

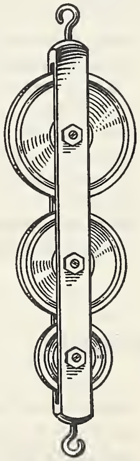


Fig. 250. Pulley, with three sheaves. They have different axles.

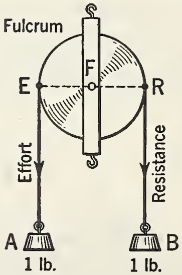


Fig. 251. Single fixed pulley. Mechanical advantage is one.

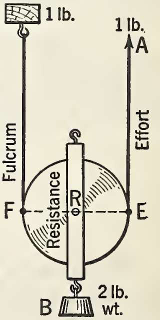


Fig. 252. Single movable pulley. Mechanical advantage is two.

other end may be attached: 1. To the movable block. 2. To the fixed block.

1. *To the movable block.* Let us refer to Fig. 253. One end of the cord is attached to the movable block, passes up over a fixed pulley, down over a movable one, then over a second fixed pulley, and so on. The effort, *E*, must pull downward a distance of 5 ft. to lift the resistance, *R*, a height of 1 ft. Hence the mechanical advantage is 5, *exactly equal to the number of strands supporting the movable block.* The strand of cord to which the effort is attached does not *support* the movable block. It does not increase the mechanical advantage, but merely changes direction.

2. *To the fixed block.* If we refer to Fig. 254, we see that one end of the cord is attached to the fixed block, and that the number of strands supporting the movable block is four. The last strand, to which the effort is attached, merely changes direction. If we let the letter *n* represent the number of strands supporting the movable block in a pulley system, then the pulley formula becomes

$$En = R.$$

It may help the memory if we note that the mechanical advantage is always an odd number when the end of the cord is attached to the *movable* block. It is an *even* number when the end of the cord is attached to the *fixed* block. In the arrangement shown in Fig. 254, the mechanical advantage is *four.* With the arrangement shown in Fig. 253, the end of the cord is attached to the movable block.

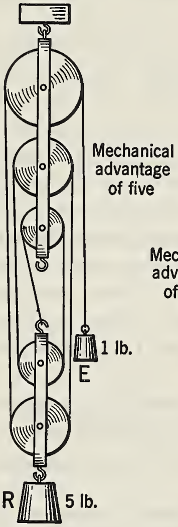


FIG. 253. Five strands support the movable block.

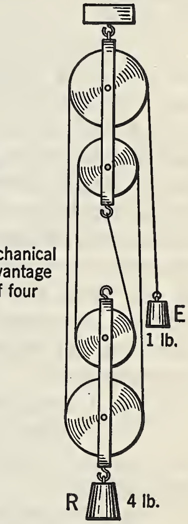


FIG. 254. Four strands support the movable block.

## 4. The Wheel and Axle

**214. How do we make use of the wheel and axle?** At some time you probably tried to open a door and found that the door knob had been removed. If you tried to turn the square bolt without the knob, you found it difficult, and gained a greater appreciation of the mechanical advantage given by this common example of the wheel and axle. The effort is applied to the circumference of the knob, and the resisting spring is applied to the circumference of the axle. Since the circumference of the knob is greater than the circumference of the axle, the mechanical advantage is one of force, because *De* is greater than *Dr*.

We notice that the simple machine

known as the *wheel and axle* consists of a wheel or crank rigidly attached to the axle which turns with it. The pupil must not confuse it with a wheel turning on an axle, like the front wheel of an automobile, which is *not* an application of this simple machine. The steering wheel of a car is an example, because the shaft to which the wheel is attached turns whenever one turns the wheel.

Let us refer to Fig. 255. We have two wheels of unequal diameter fastened together so that they can turn around the axis, *F*. In one revolution, the effort, *E*, travels a distance equal to the circumference, *C*, of the wheel. In the same time, the resistance, *R*, will travel a distance equal to the circumference, *c*, of the axle. Since $De = C$, and $Dr = c$, then the mechanical advantage, M.A., of the wheel and axle equals $C/c$. Instead of the expression,

$$\text{M.A.} = \frac{\text{circumference of wheel}}{\text{circumference of axle}}$$

we may use either of the following expressions:

$$\text{M.A.} = \frac{\text{diameter of wheel}}{\text{diameter of axle}}, \quad \text{or,}$$

$$\text{M.A.} = \frac{\text{radius of wheel}}{\text{radius of axle}}.$$

The reason is obvious, for the circumferences of the two wheels are directly proportional to their diameters or to their radii.

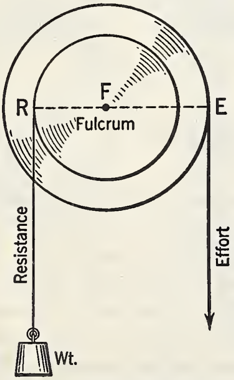


FIG. 255. Wheel and axle. Both turn on same shaft, or the same center.

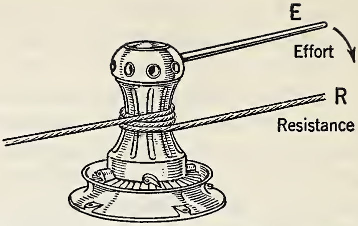


FIG. 256. The capstan finds use in hoisting anchors.

PROBLEM. A force of 100 lb. is applied to the rim of a wheel 2 ft. in diameter. What resistance can be counterbalanced upon the axle, which has a diameter of 4 inches?

*Solution.* The M.A. of this wheel and axle equals $\frac{\text{diameter of wheel (24 in.)}}{\text{diameter of axle (4 in.)}}$. Since the machine has a mechanical advantage of 6, then 100 lb. of force can counterbalance a resistance of 600 lb.

**215. What are some applications of the wheel and axle?** The *capstan* used for hoisting the anchor of a ship is an example of the wheel and axle in which the effort is applied at the ends of several levers. (See Fig. 256.) The *windlass* used for lifting water from wells is another example of the wheel

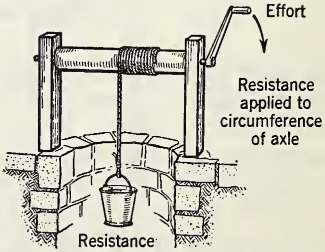

Effort
Resistance applied to circumference of axle
Resistance

FIG. 257. The windlass is used for vertical hoisting.

and axle. As the crank of Fig. 257 is turned, the rope is wound upon the axle, thus lifting the bucket and contents. The *hoisting derrick* works on the same principle, and also the steering wheels of motorboats and automobiles. In the kitchen, we find the wheel-and-axle principle applied in the meat chopper, the egg beater, the coffee grinder, and the grinding wheel.

## 5. The Inclined Plane

**216. How are the inclined plane and the ramp used?** We see men wheeling loads up an inclined gangplank, pushing weights up inclined planks to load motor trucks, and building ramps for use in stadiums, or for driving automobiles to the upper floors of garages for parking. In all these cases, it requires less effort to pull or push a resistance up the inclined surface than it does to lift it vertically. Of course, the effort has to travel the whole length of the plane in order to lift a load the height of the plane, if the *force is applied parallel to the plane.* (See Fig. 258.) Since $De$ is the length $l$ of the plane and $Dr$ is the height $h$, then the

$$\text{M.A.} = \frac{\text{length of plane}}{\text{height of plane}}, \text{ or } \frac{l}{h}.$$

Theoretically, 1 lb. of effort will push a weight of 5 lb. up an inclined plane 20 ft. long and 4 ft. high. Or,

Effort : resistance = height : length.

Problem. An inclined plane is 18 ft. long and 2 ft. high. What force will be needed to keep a weight of 2000 lb. from sliding down the plane, if we neglect friction?

*Solution.* $E : R = h : l$. By substitution, $E : 2000 = 2 : 18$. Whence, $E = 222.2$ lb. Or, by analysis, we find that the M.A. = $\frac{l}{h}$, or 9. When one has a mechanical advantage of 9, it will require $\frac{2000}{9}$, or 222.2 lb. to counterbalance 2000 lb.

A team of horses, pulling a log up inclined skids to a wagon, walks along the ground, and their pull is *parallel to the base of the plane.* Hence,

$$\text{M.A.} = \frac{\text{base of plane}}{\text{height of plane}}.$$

Other cases may occur where it is inconvenient to apply the effort parallel to the plane; then it must be applied parallel to the base or at some other angle.

**217. How do we calculate grade?** We know that the advantage of the inclined plane becomes greater as the slope is made more gentle. Engineers use the term "grade" to express the ratio of the height of an incline to its length. A hill that rises 5 ft. in 100 ft. of its length has a grade of 5%; if it rises 3 ft. in 100 ft. of its length, its grade is 3%. This is about the maximum grade for a good road; hence, in mountain regions the roads often wind about the mountain in a long spiral in order to reduce the grade. (See Fig. 259.) A zigzag path, or switchback, is sometimes used by trolley lines. At one point in the Appalachian Mountains, known as Horseshoe Curve, the Pennsylvania Railroad makes a loop, as it winds its way to a higher level.

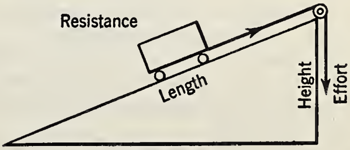
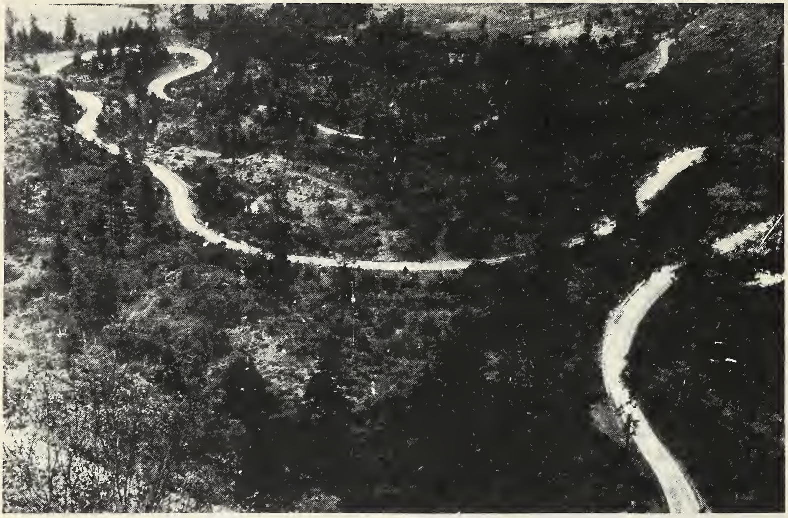


Fig. 258. The inclined plane is a much used simple machine.



*Courtesy of the U. S. Bureau of Public Roads*

Fig. 259. A road winding around a mountain is an inclined plane or a series of such planes.

## 6. The Wedge

**218. What is a wedge?** The wedge is really a double inclined plane. Since friction plays so important a part in its use, it is difficult to state any accurate law governing its mechanical advantage. Of course, the longer the wedge in proportion to its thickness, the easier it is to drive the wedge against any resistance; hence its mechanical advantage depends upon the ratio of its length to its thickness. (See Fig. 260.)

The uses to which the wedge is put vary widely. Farmers use the wedge for splitting rails and posts. Nails, pins, and needles all act as wedges when they are pushed or driven through some resisting object. Cutting tools of nearly all kinds are wedges.

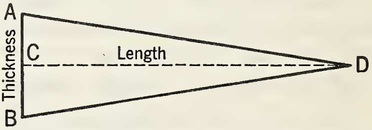


Fig. 260. The wedge is a double inclined plane.

### QUESTIONS

1. What type of machine is a brace and bit, used for boring a hole in a plank?

2. Is it easier to bore a hole with a 1-in. bit, or with one that is $1\frac{1}{2}$ in. in diameter?

3. How heavy a load can a man lift with a single fixed pulley?

4. Study Fig. 255. Show that a wheel and axle is a lever.

5. Make a list of at least six applications of the wheel and axle as used around the home.

6. What type of machine is a screw driver?

7. What type of machine is a jackknife? A cold chisel?

8. Why does a large grindstone with a short crank turn hard? What type of machine is it?

## PROBLEMS

### Group A

1. Draw a system of fixed and movable pulleys so arranged that 1 lb. will counterbalance 3 lb.

2. Make a diagram of a system of fixed and movable pulleys having a mechanical advantage of 6.

3. Two men operate a windlass. If the wheel has a diameter of 3 ft. and the axle a diameter of 6 in., what effort must each one use to overcome a resistance of 1800 lb.? How many complete turns of the wheel will be needed to lift the load 12 ft.?

4. The steering wheel of an automobile is 16 in. in diameter and the shaft to which it is attached is 1.25 in. in diameter. What resistance applied to the shaft can be overcome by a tug of 20 lb. on the wheel?

5. The handle of a screw driver is 1.5 in. in diameter and the blade is 0.375 in. wide. What is the mechanical advantage gained by the use of the screw driver? Is the screw driver a lever?

6. In a system of pulleys the effort moves 8 ft. in order to lift the resistance 1 ft. If the effort is 60 lb. and the useful load is 360 lb., what is the efficiency of the pulley system?

7. A boy can exert a force of 60 lb. How long a plank must he get if he is to roll a barrel weighing 240 lb. up into a wagon 3 ft. high? (Neglect friction.)

8. One end of a gangway 20 ft. long is 4 ft. higher than the other. It takes 75 lb. of effort to roll a 300-lb. barrel up the plank. What is the efficiency?

9. A 50-horsepower engine hoists 100 tons of coal per hour from a mine 440 ft. deep. What is its efficiency?

### Group B

10. A man uses a plank 15 ft. long to roll a barrel weighing 360 lb. to a floor 3 ft. high. If the plank weighs 100 lb., how many ft.-lb. of work did the man do in putting the plank into position? If one neglects friction, what force must the man use to roll the barrel up the plane?

11. If it is found that the man does 1200 ft.-lb. of work in rolling the barrel up the plane in Problem 10, what is the efficiency of the plane?

12. How much force must a horse exert to pull a wagon weighing 800 lb. up a 3% grade? (Note that the road rises 3 ft. for 100 ft. of length, which in this case is the base of the triangle.)

13. If an engine works at an efficiency of 100%, what H.P. engine will be required to lift 10,000 lb. to a height of 220 ft. in 5 minutes?

14. If the engine used in Problem 13 works at an efficiency of only 80%, then what H.P. engine must be used? (Of course a 1 H.P. engine does only 440 ft.-lb. of work per second, if it is working at an efficiency of only 80%.)

15. If 100 lb. of effort are applied to a wheel whose circumference is 12 ft., what resistance can be counterbalanced on an axle of 3.5 in. radius? What is the mechanical advantage of this machine?

16. A man who weighs 200 lb. carries a bag of sugar weighing 100 lb. up 3 flights of stairs to a height of 30 ft. How many ft.-lb. of work does he do? How much useful work does he do? What is his efficiency? Show by a diagram how he could arrange a fixed pulley so that two men could do three times as much work with the same expenditure of energy.

## 7. The Screw

**219. What type of machine is a screw?** Let us cut a sheet of paper in the shape of a right triangle and wind it on a pencil as shown in Fig. 261. This makes it easy to see that the screw is really an *inclined plane wound upon a cylinder.* The distance between the threads is called the *interval,* or the

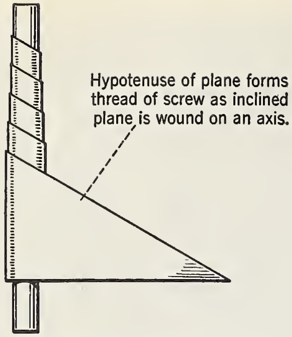

Hypotenuse of plane forms thread of screw as inclined plane is wound on an axis.

FIG. 261. The screw is an inclined plane wound on a cylinder.

*pitch* of the screw. The effort is often applied at one end of a lever which is set in the head of the screw, although it may be applied to a screw driver set in a groove of the head, or to a wrench which is attached to the head. (See Fig. 262.) While the effort describes a complete circle, the head and axis of the screw make one complete turn, and the resistance moves a distance equal to the pitch of the screw. Then,

$$\text{M.A.} = \frac{\text{circumference}}{\text{pitch of screw}}.$$

If we let $r$ equal the length of the lever, and $d$ the pitch of the screw, then we find that

$$\text{M.A.} = \frac{2\pi r}{d}.$$

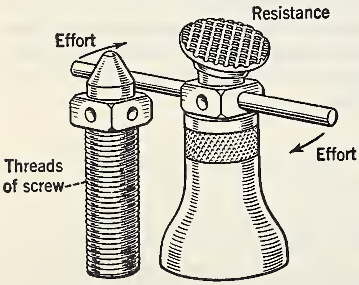
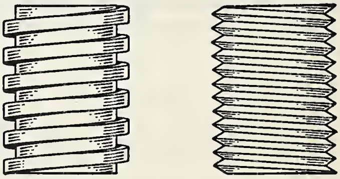


FIG. 262. Either type of head may be used with a jackscrew.

PROBLEM. The lever of a screw is 21 in. long. If the screw has 4 threads to the inch, find the M.A. of the machine. Neglecting friction, what effort is needed to lift 40,000 lb.?

*Solution.* M.A. $= \frac{2\pi r}{d}$, or $\frac{2 \times \frac{22}{7} \times 21}{0.25}$. (Since there are 4 threads to the inch, the pitch is 0.25 in.) M.A. = 528. To lift 40,000 lb., an effort of $\frac{40{,}000}{528}$, or 75.75 lb., is needed.

**220. What are some uses of the screw?** Bolts, nuts, and screws of all kinds are examples of this simple machine. When the threads on a bolt are cut so that the nut must be turned in a clockwise direction as it is tightened, the screw is said to be a right-handed one. When the nut must be turned in a counter-clockwise direction to tighten it, the screw or thread is said to be left-handed. (See Fig. 263.) The *letter press* and the *vise* are examples of the screw. The *jackscrew*, which is used for lifting buildings and other heavy objects, is a screw having a very high mechanical advantage. For measuring the thickness of paper and foil, or for finding the diameter of wire, a fine-threaded screw may be used. Fig. 264 shows the *spherometer*. The head of the screw is divided into 50 or 100 parts. If the threads are 1 mm. apart and the head is divided into 100 parts, it is evident that the point of the screw advances



Right-handed square-cut thread

Left-handed V-cut thread

FIG. 263. Right- and left-handed screws. Square-cut and V-cut threads.

only 0.01 mm. when the head is turned from one division to an adjacent one.

The *micrometer caliper* of Fig. 265 is used in a similar manner. By its use a skilled mechanic can turn a shaft in a lathe to a required diameter within a few thousandths of an inch. It can be used to find the diameter of hair or wire, or the thickness of a sheet of paper.

**221. How efficient are simple machines?** It is impossible to find any machine which is 100% efficient, because we cannot eliminate either friction or the weight of the parts of the machine. In the various types of *levers*, the efficiency may be nearly 100%, because friction is small. The efficiency of the *block and tackle* is usually not more than 60%. The rigidity of the ropes, the friction of the sheaves, and the weight of the movable block are all factors which tend to reduce the efficiency of this simple machine. If the surface of an *inclined plane* is very smooth and hard, the efficiency of the plane may be as high as 90%. Friction plays so important a part in the use of the *wedge* that it is almost impossible to estimate its efficiency. Although the *jackscrew* has a very high mechanical advantage, yet the friction is so great that its efficiency is low, possibly not more than 25%.

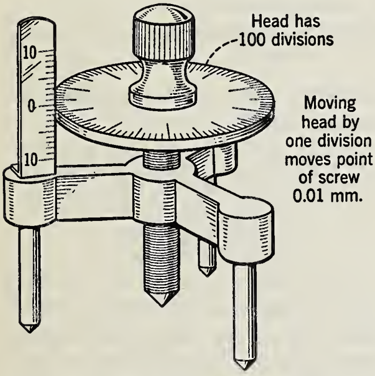


Fig. 264. The spherometer is used for accurate measurements.

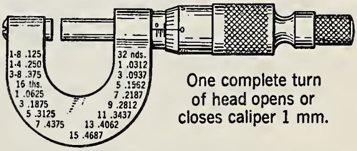


Fig. 265. The micrometer is used to measure to thousandths of a centimeter.

## 8. Compound Machines

**222. What is a compound machine?** Many complicated-looking machines are found to be a combination of two or more simple machines. A meat chopper has a crank which works on the principle of the wheel and axle as it turns a screw which forces the meat into wedge-shaped knives. In Fig. 266 we have a safe which weighs 4000 lb. to be lifted to the floor. A gangplank 20 ft. long leads to the floor, which is 4 ft. high. The M.A. of the plane is 5, but an effort of 800 lb. is still required to pull the safe up the plank. If we attach a movable pulley to the safe and a fixed pulley to the post, we have a pulley system which has a mechanical advantage of 5. Hence it will take 160 lb. of effort applied to the rope to pull the safe up the incline. The total M.A. of the two machines is 5 × 5, or 25. In nearly all cases of compound machines, the *total mechanical advantage is the product of the separate mechanical*

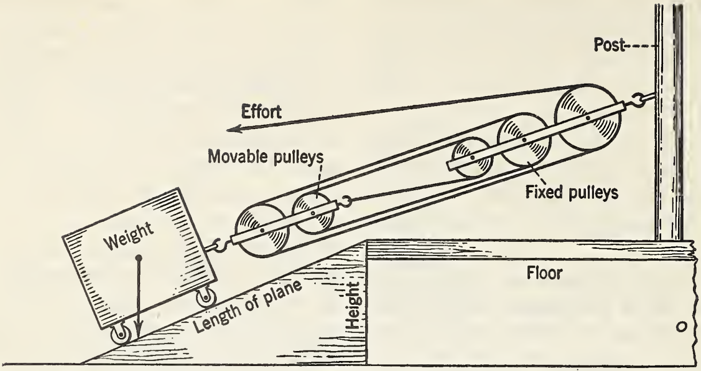

Post
Effort
Movable pulleys
Fixed pulleys
Weight
Length of plane
Height
Floor

FIG. 266. The M.A. of a compound machine is usually the product of the M.A.'s of all the simple machines of which it is composed.

*advantages*. If one machine multiplies the effort by 5 and a second machine multiplies the effort by 5, then both acting together will multiply it by 25.

**★223. How does a train of gear wheels work?** Let us refer to Fig. 267, which shows a train of gear wheels of high mechanical advantage. The effort is applied at $A$, which makes one revolution in the same time as its axle $B$; but wheel $C$ makes only that fraction of a revolution which is equal to

$$\frac{\text{number of cogs in } B}{\text{number of cogs in } C}.$$

The wheel $F$, too, will revolve only a fraction as rapidly as $D$. The wheels $A$ and $G$ are essentially wheel and axle.

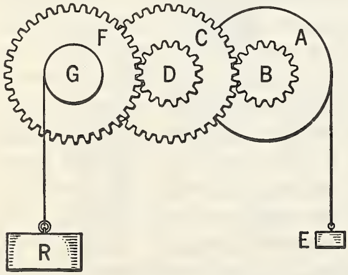


FIG. 267. A train of gear wheels. See also Figs. 802 and 804–808.

Therefore, the total mechanical advantage equals

$$\frac{\text{radius of } A}{\text{radius of } G} \times \frac{\text{No. of cogs in } C}{\text{No. of cogs in } B} \times \frac{\text{No. of cogs in } F}{\text{No. of cogs in } D}.$$

*Gear wheels* are much used to vary speed. Suppose a wheel that has 32 gear teeth is in mesh with another wheel that has only 8 teeth, or cogs. If we apply an effort to the first one, we gain speed, since the second one will make four revolutions to one of the first. If we apply the effort to the second wheel, we gain force, and have an M.A. of 4. In clocks and meters, we use a train of gear wheels for timing or for measuring. In many machines we

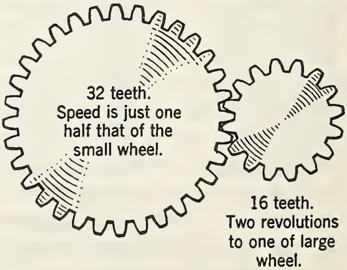

32 teeth.
Speed is just one half that of the small wheel.
16 teeth.
Two revolutions to one of large wheel.

FIG. 268. Gears are used to vary speed.

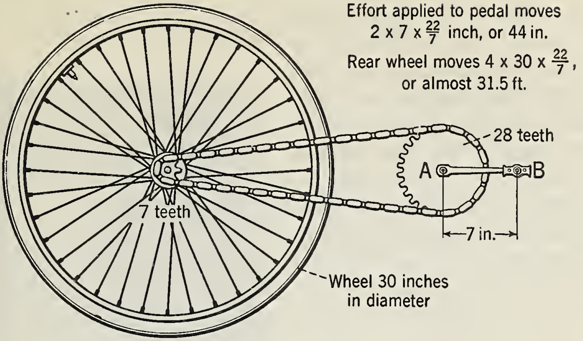

Effort applied to pedal moves
2 x 7 x 22/7 inch, or 44 in.
Rear wheel moves 4 x 30 x 22/7,
or almost 31.5 ft.
28 teeth
A
B
7 teeth
7 in.
Wheel 30 inches
in diameter

Fig. 269. The bicycle has a mechanical advantage of speed.

use gear wheels to vary speed. (See Fig. 268.)

In a bicycle, the sprocket wheels on separate shafts are connected by a chain. In Fig. 269, the front sprocket wheel has 28 teeth and the rear one only 7. Hence, for one complete revolution of the pedals, the rear wheel of the bicycle will make four complete revolutions.

When an automobile driver shifts gears, he slides one gear wheel backward or forward until it is in mesh with a gear wheel on a countershaft whose speed is controlled by the speed of the crankshaft of the engine. Since the sliding gears and the countershaft gears have different numbers of teeth, the speed can be easily varied. (See Figs. 802 and 804–808.)

★**224. How does the worm wheel work?** In this compound machine, the effort is applied to turn an endless screw, such as shown in Fig. 270. If there are 50 teeth in the wheel, then one complete turn of the *worm* or endless screw turns the wheel through 1/50 of a revolution. The resistance is applied to the axle. If we let $l$ represent the length of the crank lever upon which the effort acts, $n$ the number of teeth in the wheel, and $r$ the radius of the axle, then the mechanical advantage of the worm wheel is equal to $\frac{nl}{r}\cdot$

Some motor trucks and trolley wheels are worm-driven. The worm is turned by the engine or motor and the cogwheel drives the axle.

★**225. What is the differential pulley?** This compound machine consists of two wheels of unequal diameter, both fastened together and turning on the same axis. An endless chain connects the two wheels with a movable pulley. (See Fig. 271.) The endless chain is made of links which fit projections in the rims of the pulley wheels so that slipping is prevented.

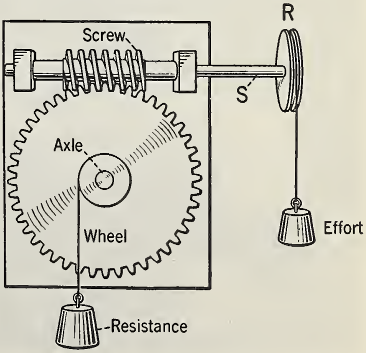


Fig. 270. The worm gear has a high mechanical advantage.

While the effort, $E$, shortens the chain by winding on the wheel $A$ a length of chain equal to its circumference, $C$, a length of chain equal to the circumference, $c$, of the wheel $B$ is unwound. The chain is thus shortened a distance equal to $C - c$, but the resistance, which is attached to the movable pulley, is lifted a distance equal to $\frac{1}{2}(C - c)$. Therefore, $De$ equals $C$, and $Dr$ equals $\frac{1}{2}(C - c)$. Whence,

$$\text{M.A.} = \frac{2C}{C - c}.$$

Fig. 272 shows a commercial type of pulley. The differential pulley finds use in garages, boathouses, and in machine shops for hoisting heavy objects. It has a very high mechanical advantage, but its efficiency is low.

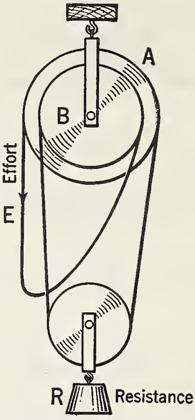


Fig. 271. Diagram of differential pulley.

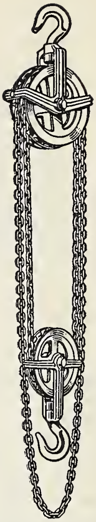
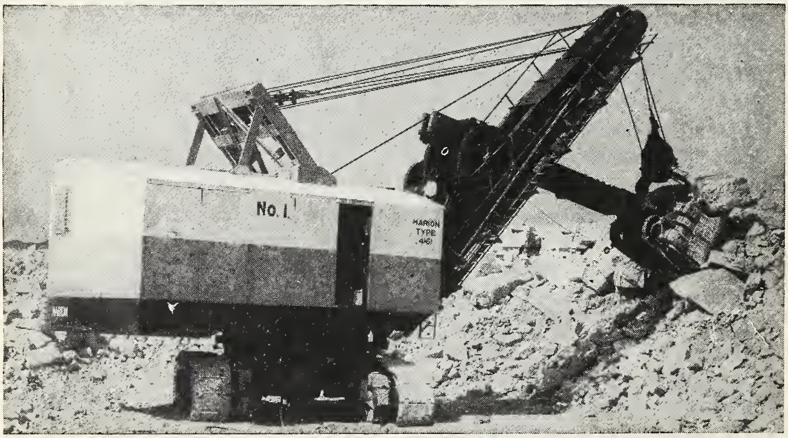


Fig. 272. Commercial differential pulley.

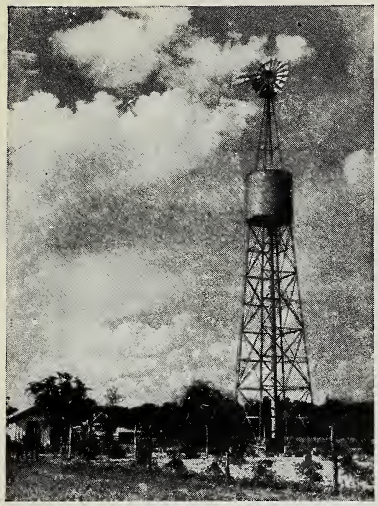
**★226. How does the steam shovel work?** One sees this compound machine everywhere. (See Fig. 273.) It is used to excavate for foundations, to make cuts or fills along railroad beds, to dig canals or dredge waterways, to scoop up ore, coal, and crushed rock and load them on freight cars, or to strip off the surface layers of earthy material that are found covering beds of coal or iron ore. The buckets are sometimes large enough to hold 6 to 8 cu. yd. of material. How many simple machines can you find in the picture?



*Courtesy of the Marion Steam Shovel Company*

Fig. 273. The steam shovel is used for excavating, building roads, and in mining operations.

## 9. The Windmill—The Water Wheel



*Courtesy of the Aermotor Corporation*

FIG. 274. The windmill is used to pump water for farm animals.

**227. How does the windmill work?** No picture of Holland seems to be complete without cows, tulips, and windmills. In this machine the kinetic energy of the wind is used to perform various kinds of work, especially the pumping of water. The blades are so set in the wheel that the force of the wind is resolved into two components, one of them causing the wheel to rotate rapidly. The large vane keeps the wheel so turned that it will be at right angles to the direction from which the wind is blowing. (See Fig. 274.)

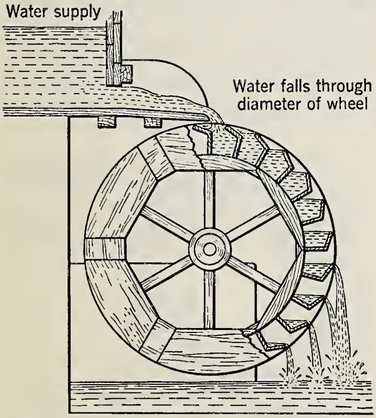


FIG. 275. The overshot water wheel is used in old mills.

**228. How do water wheels work?** *Overshot type.* Scattered throughout the country one finds a number of these old-fashioned mill wheels. (See Fig. 275.) They make use of the potential energy of water. The amount of work put into such a machine is equal to the weight of water flowing over the wheel times the distance the water falls, which is equal to the diameter of the wheel. If the supply of water is not very great and the fall is considerable, such wheels may have an efficiency as high as 80%.

★*Undershot type.* This water wheel uses the kinetic energy of running water. It finds use where the supply of water is abundant and the fall is not very great. Its efficiency is usually about 25%. The *breast-type wheel* is a modification that uses both the potential and kinetic energy of water.

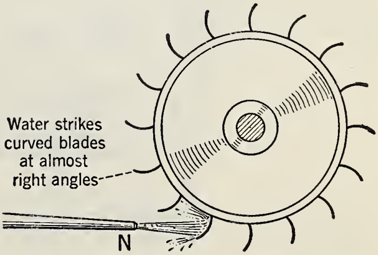
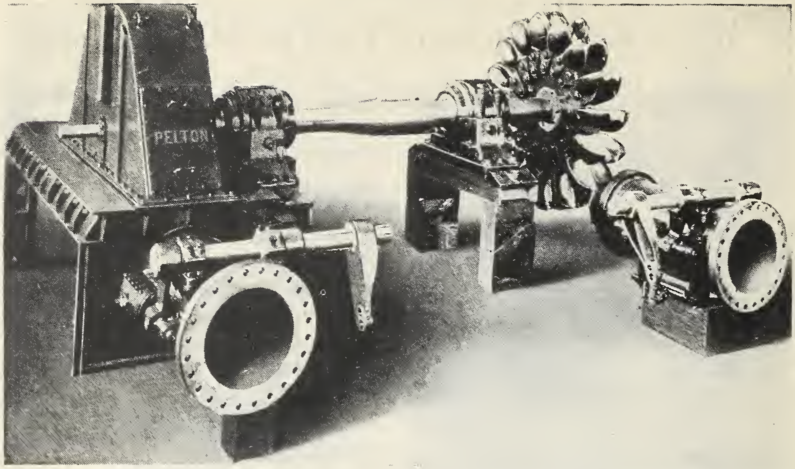


FIG. 276. The Pelton water wheel is efficient.



*Courtesy of The Pelton Water Wheel Company*

Fig. 277. The Pelton water wheel is designed to utilize the energy from water power and transform it into mechanical or electrical energy. The efficiency is high because the water strikes the cup-like blades at the proper angle.

**229. What is the Pelton water wheel?** This modification of the undershot wheel may give an efficiency as high as 80%, because a stream of water is directed from a nozzle at a high velocity against the cup-like blades. (See Fig. 276.) A large Pelton wheel designed for generating electricity is shown in Fig. 277.

The *water motor* works on the same principle as the Pelton wheel. If the pressure is fairly high, such a motor attached to a water faucet furnishes enough power to operate small lathes, grinding wheels, polishing wheels, and other appliances.

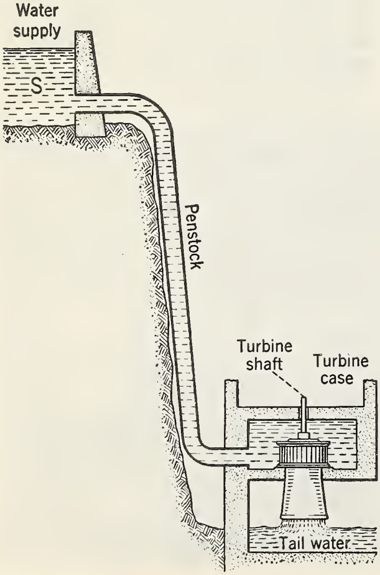

Water supply
S
Penstock
Turbine shaft
Turbine case
Tail water

Fig. 278. How a turbine is installed.

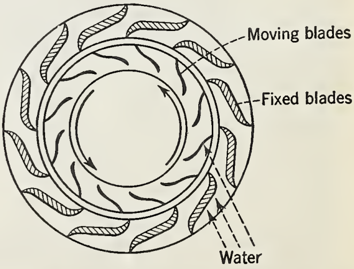
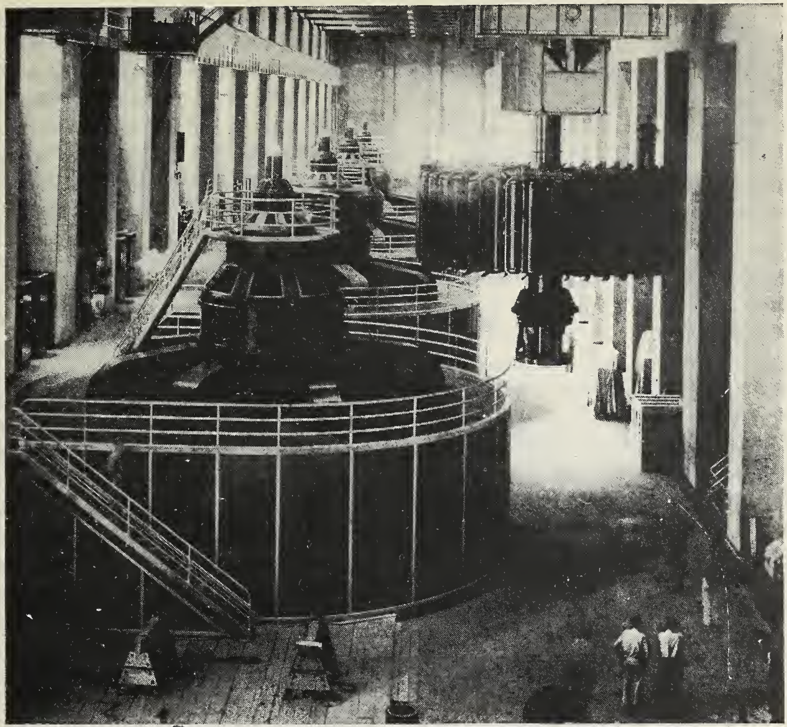

Moving blades
Fixed blades
Water

Fig. 279. The fixed blades direct the water against the movable blades.



Courtesy of the General Electric Company

Fig. 280. The energy from the so-called "white coal" pent up behind Boulder Dam is used to generate electricity. Fifteen of the hydro-electric generators are each capable of developing 115,000 H.P. Two generators are of smaller size.

**230. How does the modern water turbine work?** In large hydro-electric installations, the turbine, which was invented in France in 1833, finds extensive use. The runner of such a turbine wheel is mounted on a vertical axis in a turbine case, which receives water under high pressure by means of a penstock. (See Fig. 278.) A set of fixed blades in the turbine case directs the water against the blades of the wheel at right angles, or nearly so. (See Fig. 279.) A water turbine may have an efficiency of about 90%. A large hydro-electric installation, used at Boulder Dam, is shown in Fig. 280.

## 10. Power Transmission

**231. How can power be transmitted?** If one looks around a machine shop, he observes two types of machines: 1. *Driven machines;* 2. *Driving, or "power" machines.* How are the "power" machines connected with the

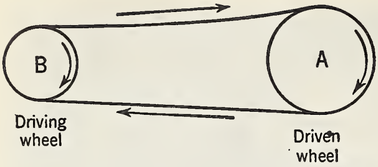


FIG. 281. Both wheels turn in the same direction.

driven machines, such as lathes, planers, grinding and polishing wheels, and saws? Several methods are in use. In the older shops, belts and pulleys were much used. If a belt is used as shown in Fig. 281, both the *drive* wheel and the *driven* wheel will turn in the same direction. If the belt is twisted, as in Fig. 282, then the wheels turn in opposite directions. The ratio of the speeds at which belt wheels rotate is *inversely* proportional to the circumferences of the wheels. For example, if wheel *A* has a diameter of 10 in. and wheel *B* a diameter of 5 in., then *B* will make *two* revolutions while *A* is making *one*.

In a study of the bicycle, we learn that a chain is used to transmit the power from one sprocket wheel to another. We have also learned that Westinghouse uses compressed air to transmit the power to the brakes. It is possible, too, to use a train of gear wheels for power transmission. In most modern shops, an electric motor is used to drive the machine. The power is transmitted to the motor from the electric generators by the use of insulated electric cables.

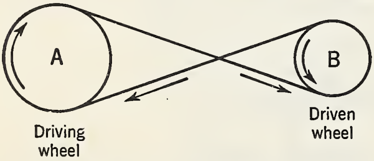


FIG. 282. With such a belt transmission, the driving wheel and the driven wheel turn in opposite directions.

The power may also come from a steam engine or a gasoline engine. In the automobile, the power from the engine is transmitted through the clutch, the transmission gears, the drive shaft, and the differential to the rear axle. (See Figs. 802–809.)

**232. Why do we have cams or eccentrics?** In the transmission of power, it is very often desirable to change a *rotary* motion into a *to-and-fro* motion, or vice versa. To accomplish this purpose, we use a *cam* or *eccentric*. Let us refer to Fig. 283 in our study of the cam. If the circular shaft shown at *A* rotates, it slides around under the vertical rod, but it does not move it up and down at all. The shaft at *B* has a projection on one side, which lifts the rod as it slides past the end and lets it spring back after it has passed. Thus the rod moves up and down as the shaft rotates. Such a device is called a *cam*. Because the projection is off center, it is sometimes called an *eccentric*, from the Latin *ex*, from, and *centrum*, center.

It would be most awkward to try to

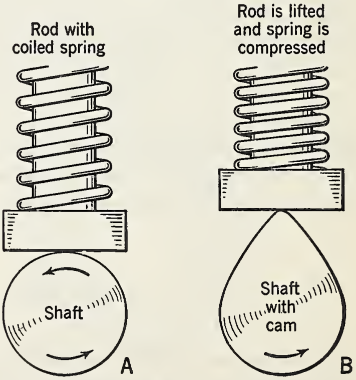


FIG. 283. The cam changes a rotary motion to an up-and-down motion.

move the feet in a circle to drive the band wheel of a sewing machine. It is easy to move the treadle up and down. (See Fig. 284.) Notice that one end of the connecting rod is fastened at *B*, a point which is *off center* on the band wheel, and that the other end is fastened to the treadle at *A*. As we push down with the toe, the end of the rod *A* moves downward and pulls the end *B* around in almost a semicircle. It will stop at *dead center* when we keep on pushing downward; but, if we hesitate, the inertia of the band wheel will carry it on past the *dead center* position. As we push down with the heel, *A* now moves upward and pushes *B* up along the other semi-circumference. There it reaches another dead center position, and we need to hesitate again to permit inertia to carry *B* past this position. Thus we push down with the toe, hesitate, push down with the heel, hesitate, and so on, as we operate the treadle of a sewing machine. The effort moves up and down and has what is called a *reciprocating* motion, but a rotary motion is imparted to the band wheel. By means of a belt, the power is transmitted from the band wheel to the hand wheel, which in turn controls another eccentric that causes the needle to move up and down. The automatic bobbin winder is another example of the principle of the cam. We shall also find that the cam is used to control the valves of the steam engine and the gas engine.

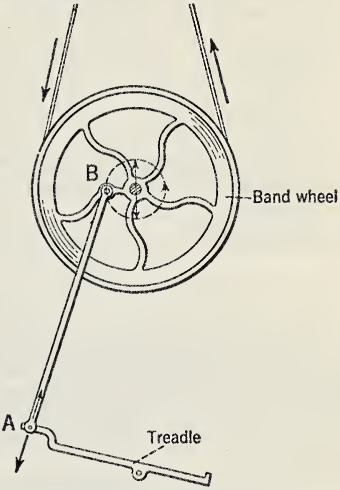


FIG. 284. Band wheel and treadle of sewing machine.

## Summary

A machine is a device used to transform or transfer energy. Theoretically, input equals output. In practice, input exceeds output. Effort times effort distance equals resistance times resistance distance.

$$\text{M.A.} = \frac{\text{resistance}}{\text{effort}}; \text{ it also equals } \frac{\text{distance effort moves}}{\text{distance resistance moves}}.$$

The efficiency of a simple machine equals $\frac{\text{useful work accomplished}}{\text{total work expended}}$.

In all classes of levers the effort : resistance = resistance arm : effort arm. $\text{M.A.} = \frac{\text{length of effort arm}}{\text{length of resistance arm}}$.

The mechanical advantage of a block and tackle equals the number of strands supporting the movable block.

In the law of the wheel and axle, $E : R$ = circumference of axle : circumference of wheel. The diameters or radii may be substituted for the circumferences.

When the force is applied parallel to the plane, effort : resistance = height of plane : length of plane. If the force acts parallel to the base, then $E : R$ = height : base.

In the use of the screw, the effort : resistance = the pitch : the circumference described by the effort.

*How many of the following terms can you define or explain? (A self-testing exercise.)*

Machine
Efficiency
Lever
Classes of levers
Pulley
Mechanical advantage of pulley
Mechanical advantage of levers
Capstan
Spherometer
Worm wheel
Steam shovel
Water wheels
Transmission of power
Pulley combinations
Wheel and axle
Law of the inclined plane
Grade
Wedge
Screw
Micrometer caliper
Differential pulley
Windmill
Water turbine
Cam
Windlass
Sewing machine
Eccentric

## QUESTIONS

1. What keeps the band wheel of a sewing machine moving during the short period between the downward and upward thrusts? Compare the relative speeds of the band wheel and the hand wheel of your sewing machine.

2. How is friction an advantage in the use of a jackscrew? In what way is it a disadvantage?

3. Make a list of ten simple machines used about the household and classify them.

4. Explain how the speed counter shown in Fig. 285 can be used to determine the number of revolutions per minute.

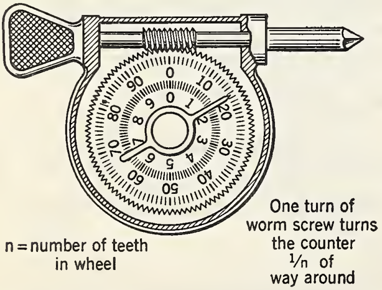

0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
6
7
8
9
n = number of teeth in wheel
One turn of worm screw turns the counter 1/n of way around

FIG. 285. The worm gear can be used as a speed counter.

5. The turnbuckle of Fig. 286 acts upon one rod which has a right-handed screw; it also acts upon another rod which has a left-handed screw. If each rod has 12 threads to the inch, how much is the space between the ends increased or decreased by one complete turn of the turnbuckle?

6. How would you change a to-and-fro motion into a rotary motion?

7. What is meant by a "high gear" bicycle?

8. What is the meaning of the expression, "The gear ratio in the differential of an automobile is 4.5"?

9. Which gives the greater braking force, brake bands acting on a 12-in. drum or on a 16-in. drum? Explain.

10. What method of power transmission has in many cases been substituted for belt drive in modern shops? How does such a change promote safety?

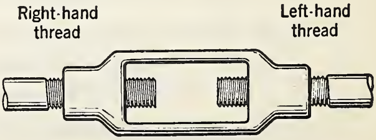


FIG. 286. The turnbuckle.

## PROBLEMS

### Group B

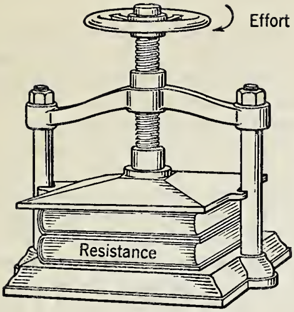


Fig. 287. The letter press.

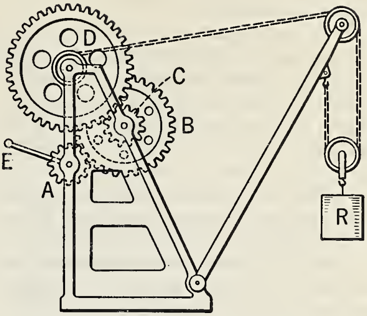


Fig. 289. The builder's crane. Is it similar to that of a wrecker car?

1. The nut that tightens the handle bars of a bicycle has 10 threads to the inch. A boy uses a wrench 7 in. long to tighten the nut and exerts a force of 40 lb. What is the force that actually tightens the nut?

2. A plumber cut 12 threads on a pipe to an inch of its length. If he uses a Stillson wrench 21 in. long to connect a valve to this pipe, what mechanical advantage does he have?

3. The pitch of a jackscrew is 0.2 in.; 20 lb. of effort are applied to a lever attached to the head of the screw. If the circumference described by the effort is 9 ft., what weight can be lifted?

4. The threads of a letter press are $\frac{3}{16}$ in. apart. If a force of 40 lb. is applied to the rim of a 14-in. wheel, what is the force of compression? (See Fig. 287.)

5. The threads of a jackscrew are $\frac{3}{8}$ in. apart. The screw is operated by a lever 2 ft., 4 in. long. If the effort applied is 100 lb., what resistance can be overcome, neglecting friction?

6. A jackscrew is operated by a lever 18 in. long. The pitch of the screw is $\frac{1}{4}$ in. If 40 lb. are required to lift a weight of 4500 lb., what is the efficiency of the screw?

7. In the hay scales of Fig. 288, the levers $AB$ and $AC$ are each 8 ft. long; $BR$ and $CR$ are each 8 in. long; $DE$ is 10 ft., and $OD$ is 1 ft.; $GF$ and $PF$ are 9 and 30 in. long respectively. What weight at $P$ is needed to counterbalance a weight of 2000 lb. on the platform?

8. The diameters of the wheels of a dif-

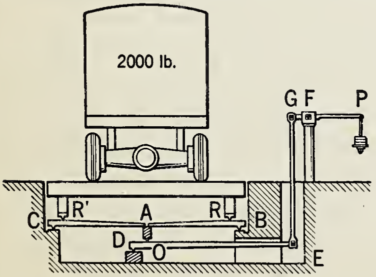


Fig. 288. The platform scales have several compound levers.

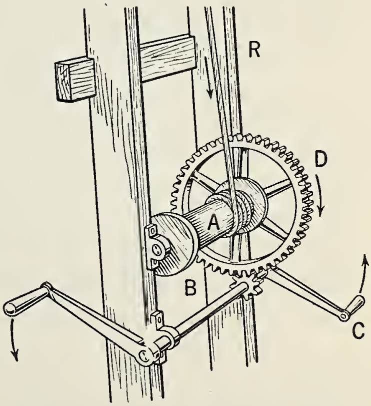


Fig. 290. A winch used with a derrick

ferential pulley are 18 and 16 in. respectively. What is the mechanical advantage? If 100 lb. must be applied to the rim of the larger pulley to lift a weight of 1200 lb., what is the efficiency?

9. A ladder used as a scaffold is 12 ft. long and weighs 100 lb. Each end is supported by a block and tackle in which 3 strands support the movable block. If the painter, who weighs 168 lb., stands 1 ft. from one block, with what force must he pull to raise the end of the ladder?

10. The front sprocket wheel of a bicycle has 28 sprockets; the rear wheel has 7. If the bicycle wheel has a diameter of 30 in., how far does the bicycle move forward with one complete turn of the pedals? If the pedal revolves at the rate of 60 times per minute, at what speed per hr. is the bicycle driven?

11. The lever of a worm wheel similar to that shown in Fig. 270 is 2 ft. long. The wheel has 90 cogs. If the axle has a diameter of 4 in., what load can be lifted by a force of 10 lb.?

12. The crane of Fig. 289 has a lever arm of 20 in. The gear wheels *A*, *B*, *C*, and *D* have 12, 60, 12, and 72 cogs respectively. If the axle has a radius of 4 in., what is the mechanical advantage of the crane?

13. Fig. 290 shows a winch for use with a simple derrick. The crank *C* is 2 ft. long. The axle upon which the rope winds is 4 in. in diameter. There are 60 cogs in *D* and 10 in *B*. If the end of the rope *R* is attached to a system of pulleys in which 5 strands support the movable block, what force at *C* will be required to lift a weight of 12,000 lb.?

# Unit Six

# *Heat*

## Preview

IN OUR STUDY OF HEAT WE ARE INTERESTED TO SOME extent in the nature of heat. We find that it is a form of energy produced by the vibration or oscillation of the molecules or of the electrons in the molecules, and that it is not a weightless fluid.

It is of more practical interest to study some of the effects which heat produces. For example, we find by experiment that solids, liquids, and gases generally increase in volume when heated, and that they contract again upon cooling. We learn, too, that heat added to a body generally causes an increase in the temperature of the body and that the temperature of the body falls as we subtract heat from it. When the heat added to a solid merely melts it, then its temperature is not necessarily increased. In a similar manner, a liquid may be changed into a vapor by the addition of heat, without any temperature change which one can detect with a thermometer. Conversely, we may subtract heat from a vapor and convert the vapor back into the liquid state. Thus we find that heat may cause a substance to expand, it may cause its temperature to increase, or it may change its state by melting it or by vaporizing it.

In the heating of our homes, we shall need to know how the heat gets from our furnace in the basement to the rooms above and how it finds its way to the various parts of the room. It will help to serve our interests if we learn how to use heat insulators to keep out heat in summer, and to keep the heat of a room from escaping to the air outside. We find, too, that we use clothing to keep the heat of the body from escaping and not because it affords us any warmth.

When we burn coal or oil to produce steam, we can utilize the heat energy to drive a steam engine. We can also put heat to work for us by exploding a mixture of gasoline vapor and air in the cylinders of a gasoline engine. It is possible to change heat energy into mechanical energy and drive some machine. Friction, which results in wasted work, produces heat. Hence mechanical energy may also be transformed into heat energy. We also use the heat energy from the oxidation of our foods in order to supply us with the energy needed to do our daily work.

# Heat — Thermometry

**233. What is the nature of heat?** It was in the year 1799 that Sir Humphrey Davy performed one of his striking experiments. He melted two pieces of ice by rubbing them together vigorously. In that way he proved that *heat is really a form of energy*. Prior to his experiment, heat was considered to be a weightless fluid called *caloric*.

From our study of the kinetic theory of matter we know that the temperature of a body rises as the velocity of its moving molecules increases. Conversely, a decrease in molecular velocity causes a fall in temperature. Rubbing our hands together increases molecular motion and warms our hands. The Indians formerly started fires by rubbing two sticks together until enough heat was produced to kindle them. Boy Scouts now use "fire sticks" in a similar manner to start fires when camping. Hence we conclude that heat may be defined as kinetic energy due to molecular motion. (See Fig. 291.)

**234. What are the sources of heat?** We really receive some heat from a number of different sources. The most important include the following:

1. *The sun.* Directly or indirectly, nearly all our heat may be traced to the sun as its origin. Plants need the heat from the sun for their growth, and animals are dependent upon plants. On a hot, sultry day in July we may appear to be getting a large amount of the sun's heat, but it is estimated that the earth as a whole receives only one two-billionth of all the heat which the sun gives off.

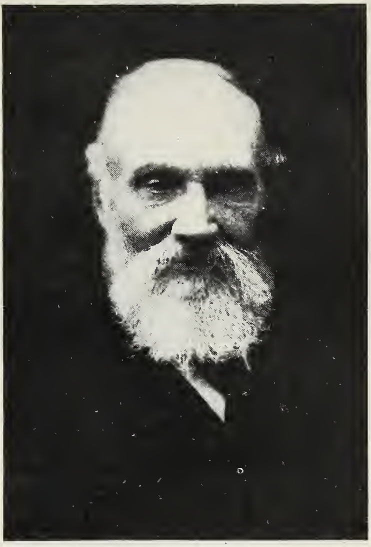


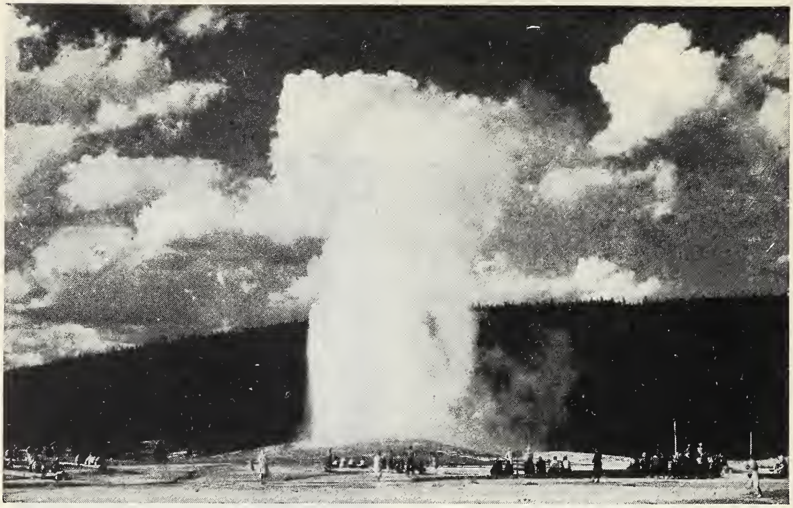
Fig. 291. Sir William Thomson (Lord Kelvin) (1824–1907) was born near Belfast, Ireland. His most important contributions in physics were in heat and electricity. He was the inventor of the absolute scale of temperature. He also invented the mirror galvanometer, the siphon recorder for receiving cable signals, and an improved mariner's compass.

2. *The earth's interior.* Molten rock issues from volcanoes and boiling water

---

## Vocabulary

Temperature, degree of heat or cold.
Centigrade, one hundred degrees.
Bore, the interior diameter of a tube.
Thermograph, a self-registering thermometer.
Clinical, for sick-bed use.
Cryogenic, pertaining to low temperature.



*Courtesy of the Department of Interior*

FIG. 292. Approximately once an hour Old Faithful Geyser erupts many gallons of water, throwing it to a height of about 125 feet. This geyser is evidence of the heated rocks that lie beneath the surface of the rocks in Yellowstone National Park.

spouts from geysers. (See Fig. 292.) The interior of the earth must be much hotter than its surface. Deep mines and wells also furnish proof that the interior of the earth is highly heated. The Calumet and Hecla copper mine is over a mile in depth. In the lower levels of this mine, the temperature is said to be about 130° F., even though compressed air is used for ventilation.

3. *Chemical action.* For our chief source of artificial heat, we depend upon the combustion of wood, coal, oil, or gas. The oxygen of the air combines with the burning fuel, while both heat and light are given off. The oxygen we breathe unites with the food we eat fast enough to supply the heat needed to keep the temperature of our bodies at about 98.6° F., summer or winter.

4. *Mechanical energy* can be changed into heat. *Friction* results in wasted work, and the energy from such wasted work is changed into heat energy. We rub the head of a match on emery paper and heat it by friction to its kindling temperature. We may climb a rope and then let it slip through our hands as we descend. Our hands will be heated decidedly and probably blistered. Brake linings sometimes burn out from the heat produced by friction. When a lead bullet is fired against a hard steel plate, it may be heated hot enough to melt the lead by *impact.* The moving bullet has kinetic energy. When it is stopped suddenly the kinetic energy is changed into heat energy. If we use a compression pump to inflate a tire, the cylinder of the pump becomes hot. Part of this heat comes from the friction of the piston moving in the cylinder, but the larger portion comes from the heat of *compression.* Gases become decidedly hot when they are compressed, and they cool off when allowed

to expand again. We shall see that this fact is important in the principle of mechanical refrigeration.

**235. Heat differs from temperature.** Although heat and temperature are related, yet we must learn to distinguish between them. A burning match has a much higher temperature than a steam radiator, but it does not give as much heat for warming a room. We may dip a cupful of boiling water from a tubful of boiling water. The temperature of the water in the cup is the same as that in the tub, but we could melt more ice with the tubful of water than we could with a cupful, because it contains *more heat.* Ten pounds of water at 80° F. will melt more ice than one pound of water at 100° F. The former has more heat, but the latter has the higher temperature.

The temperature of a body depends upon the *average kinetic energy* of all its molecules. Temperature is measured in *degrees.* The heat of a body depends upon the *sum total of all the kinetic energies* of its molecules. Heat is measured in *calories* or *British thermal units.*

A small radiator with only a few sections may have the same temperature as a large radiator with many sections, but it cannot supply so much heat to a room. (See Fig. 293.) From these observations, we learn that it is possible for a body to have a high temperature and little heat; it may have a high temperature and much heat; it may have a low temperature and little heat; or it may have a low temperature and a large quantity of heat.

**236. Is our temperature sense reliable?** We use the terms "hot," "warm," "cool," and "cold" to indicate temperature. From two or three examples, it is easy to show why they are relative and mean little. A room that feels comfortable to a person who has been resting seems uncomfortably hot to a person who has been exercising vigorously. We have three adjoining rooms, "hot," "warm," and "cold," respectively. If a person goes from the first room into the second, he will tell you that the room is "cold," but if he goes from the third into the second, he will then say that the room is "warm." His sensation of "hot" and "cold" was influenced by his environment.

Suppose you try the following experiment. Take three tumblers and fill the one at your left with *hot* water, the middle one with *warm* water, and the one at your right with *ice* water. For a few moments hold a finger of your left hand in the hot water and a finger of your right hand in the ice cold water. Then dip both fingers into the tumbler of warm water. You will have the strange sensation of feeling that the warm water is both warm and cold at the same time, for it will feel cold to your left finger and warm to your right. Because *our temperature sense is unreliable,* we need to have thermometers to measure temperature, or degree of heat.

**237. How does the air thermometer work?** Once again we meet the famous Galileo. This time we find that he is the inventor of the air thermometer. It consists of a glass bulb with a long tube attached. The tube dips into some colored liquid, as shown in Fig. 294. When the bulb is warmed, the air in-

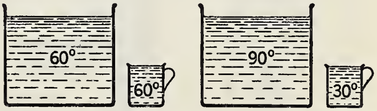


FIG. 293. In one case the temperatures are the same, but the quantities of heat are unequal. In the other case, both are unequal.

side the bulb expands and some of it escapes. As the air in the bulb cools, some of the liquid rises in the tube. Such a thermometer is very sensitive to temperature changes, but of course it has to be corrected each time for changes in air pressure.

**238. How is the mercury thermometer made?** To construct a mercury thermometer, a bulb is blown at one end of a thick-walled capillary tube. (See Fig. 295.) The bulb and part of the stem are then filled with mercury. The bulb is then heated until the mercury expands and fills the tube, which is sealed at *A*. All the air is thus expelled from the tube, leaving the mercury free to expand or contract with changing temperatures. A bulb and partially filled tube needs only to be graduated to make it a finished thermometer. While the mercury thermometer is not so sensitive as the air thermometer, it is not affected by changes in pressure.

**239. How do we graduate a thermometer?** Before one can graduate a thermometer, some "fixed points" or definite temperatures must be selected. The *freezing point* and the *boiling point* of water are *two fixed temperatures* which can be easily determined.

The bulb and lower portion of the stem of the thermometer constructed as described in Section 238 are packed in a funnel containing melting ice. It is more convenient to use melting ice than freezing water, and *both have the same temperature.* The lowest point to which the mercury falls is marked the *freezing point.* Such a fixed point may be etched on the glass of the thermometer tube, or upon some scale to which the thermometer is firmly attached. (See Fig. 296.)

To find the *boiling point,* the thermometer is suspended in the steam arising from boiling water. (See Fig. 297.) The highest point to which the mercury rises is marked *boiling point* on the thermometer scale. One precaution must be taken. The boiling point of water varies with the pressure; hence, for this work the water must be

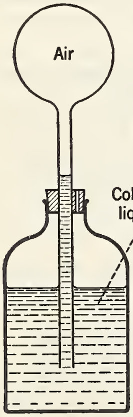


Fig. 294. The air thermometer was one of Galileo's inventions.

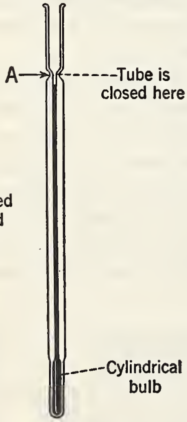


Fig. 295. A small-bore tube used for making a mercurial thermometer.

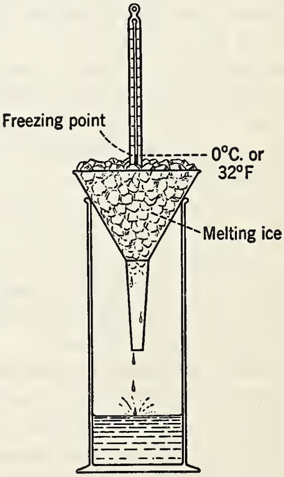


Fig. 296. Checking a thermometer for freezing point.

boiling when it is under a pressure of exactly 76 cm. of mercury.

**240. How are degrees marked on a thermometer?** After the *fixed points* have been marked upon a thermometer, it must then be divided into degrees. Several scales, in which the degrees are different, have been devised, but we shall study only two, the Centigrade and the Fahrenheit.

*Centigrade scale.* This scale, which was devised by Celsius, is used almost exclusively in foreign countries. It is used for *scientific* work throughout the United States. On a Centigrade thermometer the freezing point is marked *zero*, and the boiling point is marked *100*. The space between the fixed points is divided into 100 (*centum*, hundred; *gradum*, degree) equal spaces called *degrees.*

*Fahrenheit scale.* This scale, which was devised by Fahrenheit, is used in the United States for weather observations. On a Fahrenheit thermometer, the freezing point is marked 32, and the boiling point is marked 212. The space between these two fixed points on a Fahrenheit thermometer is divided into 180 equal degrees.

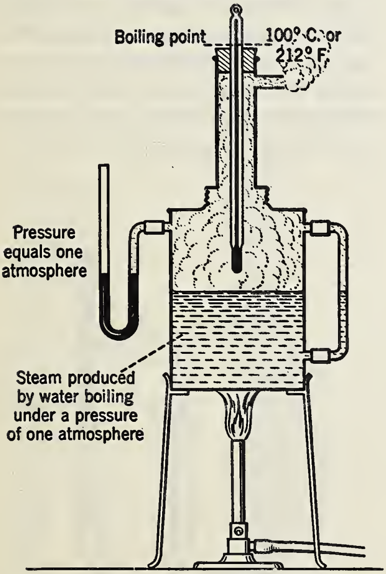

Boiling point
100° C. or 212° F.
Pressure equals one atmosphere
Steam produced by water boiling under a pressure of one atmosphere

Fig. 297. Checking the boiling point as one fixed point of a thermometer.

**241. How can one convert one reading into another?** Sometimes we must change meters to yards, or inches to centimeters. In a similar manner, it is sometimes necessary to change Fahrenheit thermometer readings into Centigrade readings, or vice versa. To do so, it is necessary to start with the fact that 0° C. and 32° F. are really the same temperature, and that 100° C. is the same as 212° F. Between the boiling point and the freezing point on a Centigrade thermometer we have 100 degrees and between the same points on a Fahrenheit thermometer we have 180 degrees. Therefore 100 Centigrade degrees equal 180 Fahrenheit degrees. Whence, 1 Centigrade degree equals 1.8 Fahrenheit degrees. (See Fig. 298.)

If a Centigrade thermometer reads

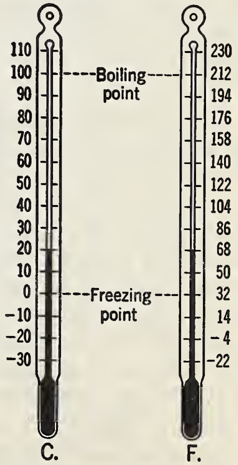

110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
Boiling point
Freezing point
230
212
194
176
158
140
122
104
86
68
50
32
14
−4
−22
C.
F.

Fig. 298. How Fahrenheit and Centigrade thermometers compare.

20°, the temperature is 20 Centigrade degrees above the freezing point. But it is also 36 (20 × 1.8) Fahrenheit degrees above the freezing point. If it is 36 Fahrenheit degrees above the freezing point, which is 32° F., then the Fahrenheit thermometer must read 68° when the Centigrade thermometer reads 20°. In general, then,

*To change Centigrade readings to Fahrenheit readings, we multiply the Centigrade readings by 1.8, and add 32.* Conversely, *to change Fahrenheit readings to Centigrade readings, subtract 32 from the Fahrenheit reading and divide by 1.8.* One may use the formula given in Appendix A. The following short cut may be used: To change Centigrade readings to Fahrenheit, add 40 to the Centigrade reading, *multiply* the sum by 1.8 and subtract 40. To change Fahrenheit readings to Centigrade, add 40 to the Fahrenheit reading, *divide* the sum by 1.8, and subtract 40.

PROBLEM. Change − 10° C. to Fahrenheit. Change − 58° F. to Centigrade.

*Solution.* $-10 \times 1.8 = -18$; $-18 + 32 = 14$. Hence, − 10° C. equals 14° F. In problem No. 2, $-58 - 32 = -90$; $-90 \div 1.8 = -50$° C. Therefore, − 58° F. equals − 50° C.

**242. How is the mercury thermometer limited?** Since mercury freezes at a temperature of about − 39° C., it cannot be used to measure temperatures below that point. Rear-Admiral Byrd needed an alcohol thermometer for use in the polar regions, where much lower temperatures are common. The freezing point of ordinary alcohol is − 130.5° C. It is usually colored red or blue so that it can be seen more easily.

For *very* low temperature measurements, a gas thermometer is used. (See Fig. 299.) The bulb contains hydrogen, which contracts upon being cooled. The mercury in the bent tube rises at *B* and falls at *C*. Then the tube is lowered until *B* drops to its former level. The temperature is calculated from the *change of pressure* needed to keep the volume of the hydrogen gas constant.

The boiling point of mercury is 357° C. Hence the mercury thermometer is not suitable for measuring *high* temperatures. Several methods of measuring high temperatures are in use. Sometimes a gas thermometer is used. Platinum changes its electrical resistance with the temperature, and a *platinum resistance* thermometer is used to measure temperatures by measuring the amount its resistance changes. Two metals in contact will produce electricity when heated. Temperatures are sometimes measured by measuring the amount of electricity such a *thermo-couple* produces.

**243. There are special thermometers for special uses.** 1. *Clinical.* The thermometer used by physicians for taking the temperature of the human body needs only a short scale, because our normal temperature is 98.6° F.,

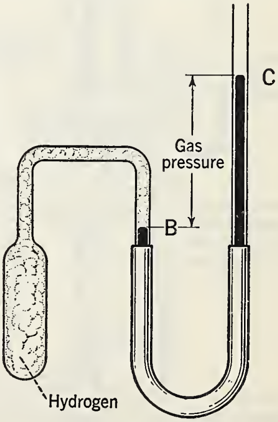


FIG. 299. A gas thermometer.

and it never varies more than a few degrees in either direction. Since the scale of the *clinical* thermometer is usually graduated from 92° F. to 110° F., it is possible to have the degrees far enough apart so that the scale can be read when divided into *tenths* of a degree.

In still another way the clinical thermometer is different. The tube is *constricted* to reduce the size of the bore just above the cylindrical bulb. The mercury forces its way past this constriction as it expands, but the cohesion of the mercury molecules is not great enough to pull the mercury column back past the constriction. Hence the top of the mercury column remains at the highest reading, which can be read leisurely. The thermometer is then given several quick jerks to shake the mercury back into the bulb to be ready for the next reading. (See Fig. 300.)

2. *Maximum thermometers.* Such thermometers are used by the Weather Bureau to show the highest temperature within a given time, usually 24 hours. One type of maximum thermometer is constructed like the clinical thermometer. It is set at a certain hour each day by shaking the mercury down into the bulb. Then as the temperature increases, the mercury rises in the tube and stands at the highest temperature reached during the day. In another type, the mercury pushes a little steel index upward as it rises. The friction of this index against the inner walls of the tube holds it at the highest recorded temperature. To set the thermometer for a subsequent reading a magnet is used to drag the steel index down into contact with the mercury.

3. *Minimum thermometer.* The bulb of one type of *minimum* thermometer is filled with alcohol. The surface tension of the alcohol drags a small steel

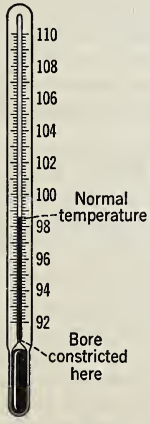

110
108
106
104
102
100
Normal
temperature
98
96
94
92
Bore
constricted
here

Fig. 300. The clinical thermometer.

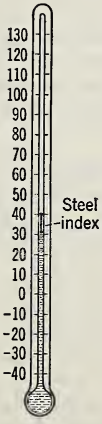

130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Steel
index

Fig. 301. A minimum thermometer.

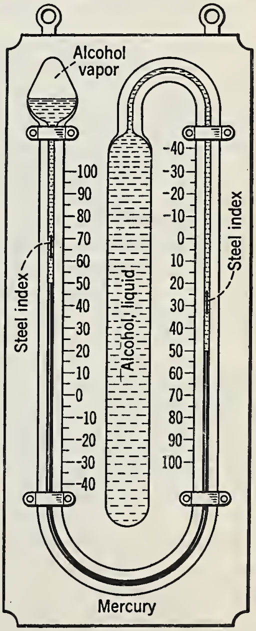

Alcohol
vapor
Steel index
Alcohol liquid
Steel index
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
Mercury

Fig. 302. A maximum-and-minimum thermometer.

index along the tube as the alcohol contracts. This index is left at the lowest temperature reading for the time interval, because the alcohol flows past it when it expands again. (See Fig. 301.) This thermometer, too, is set by the use of a magnet.

★4. *Maximum-and-minimum thermometer.* By the use of bent tubes like those shown in Fig. 302, both the maximum and minimum temperatures can be read from the same instrument. One bulb contains alcohol and alcohol vapor. Since the alcohol vapor is easily compressible, the tube is not broken as the mercury column in the bent tube is pushed backward and forward.

5. *Self-registering instruments.* The thermometer of Fig. 303 is a metal type which carries an ink pointer to record the temperature on a graph, which consists of a sheet of ruled paper wound on a cylinder. A clock-work mechanism turns the cylinder through one complete revolution per week, while the pointer traces a continuous line which shows the temperature at any particular day or hour of the week. See graphs of Figs. 304 and 305.

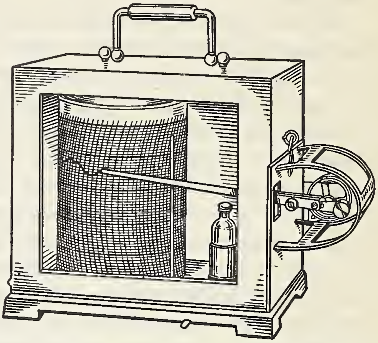


FIG. 303. A thermograph, or self-recording thermometer.

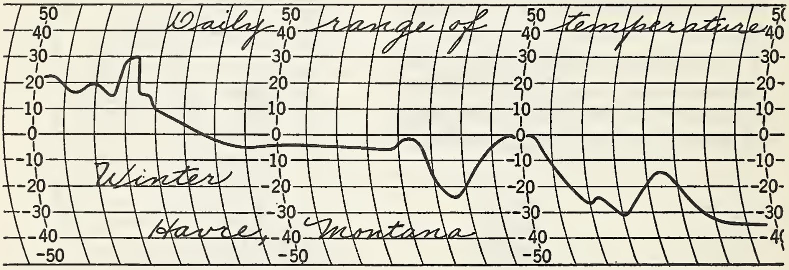


FIG. 304. The graph shows a decided cold wave during a week in January at Havre, Montana.

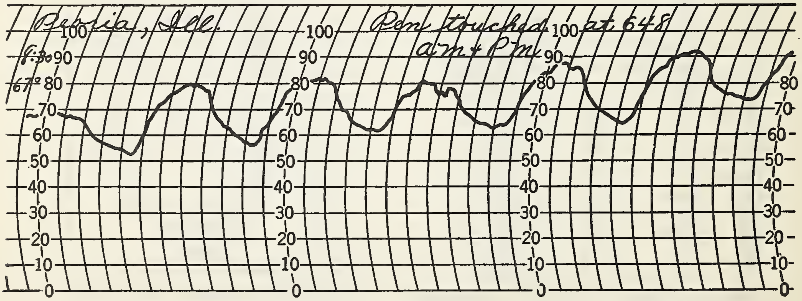


FIG. 305. The graph shows daily variations in temperature at Peoria, Illinois.

## Summary

The sun, the interior of the earth, chemical action, friction, impact, and compression are the chief sources of heat.

Heat is the sum of the kinetic energies of all the molecules of a body. The temperature of a body is the average kinetic energy of its molecules.

Sensation is an unreliable method of determining temperature. A thermometer is an instrument devised for that purpose.

To change Centigrade readings to Fahrenheit, multiply the reading by 1.8 and add 32; to change Fahrenheit readings to Centigrade, subtract 32 from the Fahrenheit reading and divide by 1.8.

Special thermometers are constructed to show the maximum or minimum temperature for any given period, usually 24 hr.

The clinical thermometer is used to find the temperature of the human body. Self-registering thermometers keep a continuous record of the temperature for any given period.

*How many of the following terms and phrases can you define or explain? (You should be allergic to most of them.)*

Sources of heat
Heat *versus* temperature
Air thermometer
Mercury thermometer
Fixed points
Centigrade scale
Fahrenheit scale
Thermometer conversions
Clinical thermometer
Maximum thermometer
Minimum thermometer
Thermograph

## QUESTIONS

1. Why do sparks sometimes fly from a car wheel when the brakes are applied?
2. Sometimes the brakes of an automobile catch fire when the driver is descending a long grade. Explain, and tell how such a condition may be avoided.
3. Give an example of a body that has a low temperature and a large quantity of heat. Give an example of a body that has a high temperature but contains little heat.
4. Why must the air thermometer be corrected for pressure changes?
5. Why must a thermometer tube be of uniform bore?
6. Should a thermometer have a spherical or a cylindrical bulb? Give a reason for your answer.
7. Air must be cooled before rain falls. At the tropics the air currents are descending. How do you account for the arid regions in Australia?
8. How does the size of the bulb of a thermometer affect its sensitiveness? What other factor affects the sensitiveness of an ordinary thermometer?
9. What properties should a liquid have to make it suitable for use in a thermometer?
10. Occasionally a train is delayed because of a "hot box." What is a "hot box," and how is it caused?
11. Why does the mercury in a thermometer drop a fraction of a degree before it begins to rise when the bulb is plunged into hot water?
12. What objection is there to the use of boiling water for sterilizing a clinical thermometer after use?
13. A mother uses a clinical thermometer and finds that her little girl has a temperature of 102° F. She lays the thermometer aside and rushes to telephone the doctor. The following morning she takes her son's temperature. What will be its probable reading?
14. How should a thermometer be held while it is being read?
15. How accurate are the thermometers given away for advertising?
16. Does the mercury in a thermometer ever freeze in cold climates?

## PROBLEMS

### Group A

1. A clinical thermometer is graduated to give Centigrade readings. What Centigrade readings correspond to 92° F? To 98.6° F.? To 110° F.?

2. Room temperature is considered 68° F. What is it Centigrade?

3. The temperature of the electric arc is about 3600° C. What is its Fahrenheit temperature?

4. If alcohol freezes at − 130° C., calculate its freezing point on the Fahrenheit scale.

5. Change − 182° C., the boiling point of liquid air, to Fahrenheit.

6. If tungsten melts at 5432° F., what is its melting point on the Centigrade scale?

7. Reduce the following Fahrenheit temperatures to Centigrade: 190° F.; − 299° F.; 6332° F.; − 20° F.; 70° F.; − 450° F.; and − 252° F.

8. Reduce the following Centigrade readings to Fahrenheit: 1500° C.; − 273° C.; − 200° C.; − 40° C.; 4000° C.; 1780° C.; 1050° C.; 357° C.

# Heat — Expansion

**244. What are some of the things that heat can do?** When you try to get a job, one of the first questions you will be asked is, "What can you do?" As we begin our study of heat, we want to know its effects. We find that heat can accomplish several things.

1. As heat is absorbed by a body, the temperature of the body generally rises. Water in a pan over a gas stove rises in temperature as it absorbs heat.

2. Heat absorbed by a solid may cause the solid to melt, or to change from the solid to the liquid state.

3. Heat absorbed by a liquid causes the liquid to evaporate or to change from the liquid state into a vapor. For example, ice melts when heated, and the continued addition of heat changes the water into steam or vapor.

4. The size of an object nearly always increases when it is heated. Mercury in a thermometer expands. Bodies not only increase in length when heated, but they expand in all directions.

5. Heat causes many chemical changes to occur. The cooking of foods is an example, and many chemical reactions in the laboratory are started by the application of heat.

6. Heat may be used to produce an electric current, particularly when two different metals in contact are heated.

7. Heat produces many physiological effects, both in plant and animal life. Without heat, the world would soon become barren.

**245. Heat makes solids expand.** If you are a good observer, you will have noticed that telephone wires sag more in summer than in winter. You will find, too, that the spaces between the ends of railroad rails are wider in winter than in summer. Sometimes wires used for fences and for telephone or telegraph lines contract so strongly in cold weather that they break. With few exceptions, *solids expand when they are heated and contract when cooled.* They not only increase in length, but they also increase in breadth and thickness.

At room temperature, the iron ball of Fig. 306 passes easily through the ring. If we heat the ball strongly, it cannot pass through the ring at all.

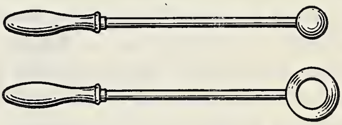


FIG. 306. The cold ball passes through the ring, but the heated ball cannot.

## Vocabulary

CORRUGATED, formed into folds or furrows.
COEFFICIENT, a number used as a factor.
COMPENSATED, opposing forces are balanced.
ALLOY, a substance composed of two or more metals.
SUPERFICIAL, pertaining to surface or area.
SPALL, a piece or fragment of broken rock.
INVAR, an alloy of low coefficient of linear expansion.
ELINVAR, a steel alloy used in making hairsprings and balance wheels for watches.
THERMOSTAT, device to regulate temperature.

Next, let us heat the ring strongly, and we find that the heated ball will pass through the ring. If we pour cold water on the ring to cool it, the ring will contract so much that the hot ball cannot pass through it. Rubber is one of the important exceptions to the general rule that solids expand when heated and contract when cooled. A few others are known.

**246. How much do solids expand?** To answer a question of this kind, it is necessary to experiment. In the laboratory it can be shown that one foot of aluminum wire will expand more than twice as much as one foot of iron wire, if each one is heated one degree. That number or factor which shows the *actual increase in unit length of a solid when it is heated one degree is called its coefficient of linear expansion.* For example, 1 ft. of aluminum will expand 0.000023 ft. when its temperature is raised 1° C. The same increase in temperature will cause 1 ft. of iron to increase 0.000011 ft. Table 10 in Appendix B shows the coefficient of expansion for several solids. This table gives the coefficient of expansion for *Centigrade degrees*. The coefficient of expansion for *Fahrenheit degrees* will be just $\frac{5}{9}$ as much. Two of the several methods for finding the coefficient of expansion of solids experimentally are given in the laboratory manual designed to accompany this textbook.

If 1 ft. of aluminum wire expands 0.000023 ft. when heated 1° C., then 10 ft. will expand 10 times as much, or the increase will be 0.00023 ft. If 10 ft. of wire are heated 10° C., the increase in length will be ten times as great as for 1° C., or 0.0023 ft. Whence, we conclude that the *total increase in length of a solid when heated must be equal to its length times its change in temperature times its coefficient of linear expansion.*

Problem. An iron rod is 65 cm. long at 0° C. How much will it expand when heated to 80° C.? What will be its length at 80° C.?

*Solution.* From the table we see that 1 cm. of iron expands .000011 cm. when heated 1° C.; 65 cm. will expand 65 × .000011 cm., or .000715 cm., when heated 1° C.; the change in temperature is 80 degrees, so the actual increase would be 80 × .000715 cm., or .0572 cm. The length of the rod at 80° C. would be 65.0572 cm. (Original length plus expansion.)

**247. Do solids expand in all directions?** It is important to keep in mind the fact that solids when heated not only increase in length but they also expand in width and thickness. The *coefficient of superficial expansion*, or the increase in unit area per degree, is slightly more than *double* the linear coefficient. The buckling of metal roofs and concrete sidewalks when strongly heated is due to the expansion in area. The *coefficient of cubical expansion*, or the increase in volume when a solid is heated one degree, is slightly more than *three times* the coefficient of linear expansion.

**248. What is the effect of unequal heating?** If boiling water is poured quickly into a thick-walled glass tumbler, the tumbler will probably crack. The inside is heated and expands before the outside does. Men sometimes crack up large boulders by building a fire around them to heat them strongly. Fragments and spalls of rock then split and break off when cold water is thrown upon the hot boulder. Unequal heating often causes solids to break, because one portion expands more than another.

**249. Can expansion of solids be made useful?** Sometimes walls spread apart and threaten to fall. A long iron

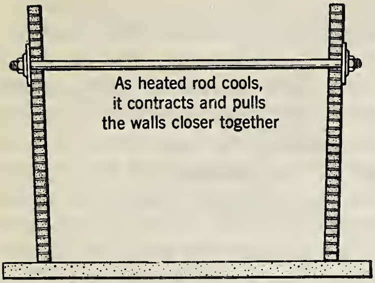

As heated rod cools,
it contracts and pulls
the walls closer together

Fig. 307. As the heated rod cools it contracts and straightens the walls.

rod may be put through, heated strongly, as shown in Fig. 307, and the nuts at the ends screwed on tightly. As the rod contracts upon cooling, the walls are pulled together. Carriage tires are sometimes heated before they are put on the wheel. As they cool, they shrink and become tight fitting. Rivets are heated red hot before they are used to rivet steel plates together. As they cool they contract and make a very tight joint. The expansion and contraction of metals is used to open and close valves.

In one type of *automatic* water heater, a rod of invar, a metal of low coefficient of linear expansion, is used inside a copper tube to regulate the amount of gas needed to keep the water in the hot-water tank at the desired temperature. As the copper tube expands it gradually closes the valve regulating the flow of gas, and permits it to open again as the copper rod cools. (See Fig. 308.)

**250. How do engineers cope with the expansion problem?** One manufacturer of wire fence for the farm uses spring steel, and the wires are somewhat wavy instead of being straight. If the metal beams used to support a long bridge were firmly fastened to each pier, the expansion and contraction would destroy the piers. Fig. 309 shows how engineers fasten one end of a bridge and mount the other end on rollers to permit it to expand and contract.

Concrete blocks for roads and sidewalks have expansion joints, which may be filled with bitumen, a material that is somewhat plastic. The floor openings around the steampipes are large enough to allow the steampipes to expand and contract without lifting the floor. The manufacturers of "Pyrex" glass learned how to make a product with a very low coefficient of expansion, thus reducing the danger

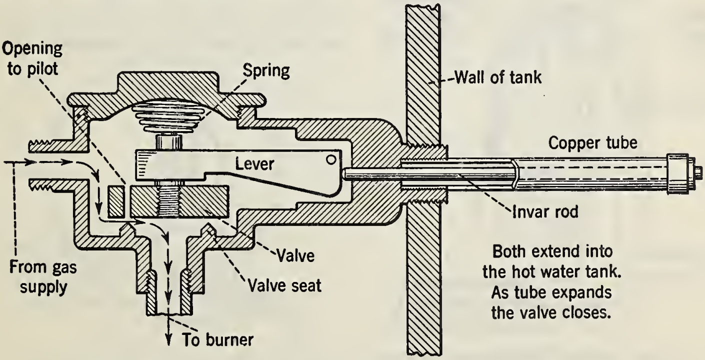

Opening to pilot
Spring
Wall of tank
Copper tube
Lever
Invar rod
From gas supply
Valve
Valve seat
To burner
Both extend into the hot water tank. As tube expands the valve closes.

Fig. 308. The thermostat is used to keep water temperature constant.

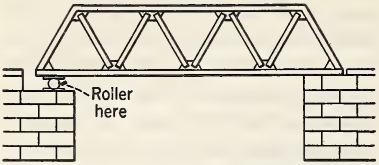

Roller
here

Fig. 309. Bridge expands when heated. Rollers permit one end to move.

of breakage from heat. This glass finds extensive use in chemical laboratories, and thick glass baking dishes made of "Pyrex" glass can be put into a hot oven with little danger of breaking. The coefficient of expansion of "Pyrex" is only about one-third that of ordinary glass.

The two wires that lead in to the filament in an electric bulb must be sealed in the glass so perfectly that no gases can get into the bulb or escape from it. Hence they must have the same coefficient of expansion as glass, or unequal expansion and contraction will break the seal. For a long time the expensive metal platinum was the only metal known which has the same coefficient of expansion as glass. Research engineers attacked the problem and developed an alloy which can be used instead of the expensive platinum. An alloy of nickel and iron, sheathed in copper is now used for the "lead-in" wires of electric bulbs. (See Fig. 310.)

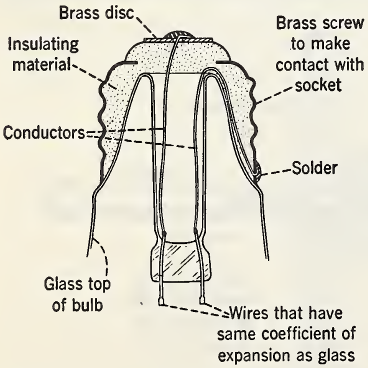

Brass disc
Insulating material
Brass screw to make contact with socket
Conductors
Solder
Glass top of bulb
Wires that have same coefficient of expansion as glass

Fig. 310. The "lead-in" wires have the same coefficient of expansion as glass.

**251. How do radiator valves work?** Since two things cannot occupy the same place at the same time, we cannot get any steam from the furnace into our radiators, unless we make provision for the air in the radiators to get out. But we must not let the steam escape. To see how one can manage to let the air escape, but keep the steam inside, let us refer to Fig. 311. The metal capsule *C* contains a liquid which changes to vapor when it is heated by steam. The vapor then exerts pressure and pushes the top of the capsule upward until the metal rod on its top closes the opening in the valve. The elasticity of the corrugated metal of which the sides of the capsule are made permits the top to move upward when the pressure inside the capsule increases, but it springs back to its former position as the vapor inside condenses again.

One type of valve has been devised which permits some vapor to escape and increase the relative humidity of the room.

**252. What is the compound bar?** Suppose that we have two flat strips of brass and iron riveted firmly together to make a *compound bar*, as

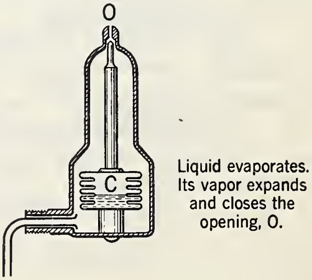

O
C
Liquid evaporates.
Its vapor expands
and closes the
opening, O.

Fig. 311. The radiator valve.

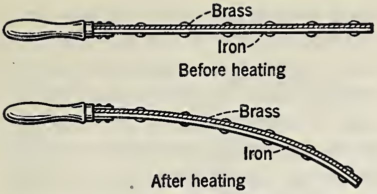
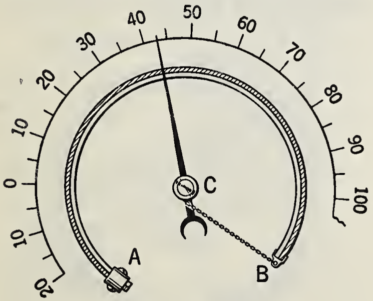


FIG. 312. The compound bar.

shown in Fig. 312. If they are straight before heating, they will curve when heated, because the brass expands more than the iron does. The compound bar will straighten out again when cooled, and it will even bend in the other direction if it is cooled greatly. Of course, such a compound bar may be made by riveting or soldering together any two metals that have different coefficients of expansion.

**253. For what purposes are compound bars used?** 1. *Metallic thermometers.* From Fig. 313, we see that one end *A*, of a circular compound bar is attached firmly to the base of the thermometer. The end *B* is fastened to a pointer which is pivoted so that it can rotate about the axis, *C*. The metal on the outside of the compound bar has the greater coefficient of expansion. When heated, it expands more and pushes the pointer in a clockwise direction along the scale. Many oven thermometers are of this type.



Compound bar bends inward when heated

FIG. 313. This metal thermometer is a compound bar.

2. *The thermostat.* To keep a room at a nearly constant temperature, a *thermostat* (temperature stationary) is often used. From Fig. 314 we see that it operates by means of a compound bar much as the metallic thermometer does. One end of the bar is fixed. The other end is fastened to a pointer which moves back and forth between the points *C* and *C′*. If the room grows too warm, the pointer makes an electrical contact at *C*, and the drafts of the furnace are automatically closed. They are opened again when the room cools down enough for the pointer to make another electrical contact at *C′*. In this way, the temperature of a room may be kept at 68° F., for example, within a variation of one or two degrees.

3. *The balance wheel.* When the balance wheel of a watch expands in summer, the watch runs too slowly. The higher priced watches have *compensated* balance wheels. As the radius of such a wheel, Fig. 315, expands and

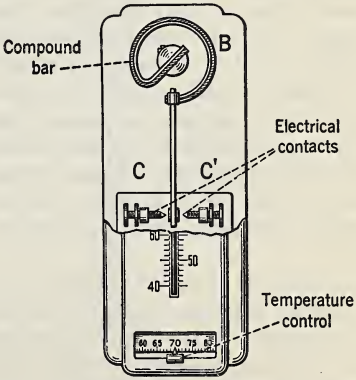


FIG. 314. A thermostat is designed to keep the temperature constant.

tends to slow up the movement, the compound bars bend and throw the ends $W$ and $W'$ inward just far enough to accelerate the motion. It is possible to so adjust such a balance wheel that the effect of lengthening the radii is just nullified by the inward movement of the loaded ends of the bars. Such a watch is not affected by temperature changes.

**254. How is elinvar used?** Dr. Guillaume, who developed elinvar was awarded the Nobel prize for his accomplishment. At least one manufacturer of high-grade watches uses the steel alloy known as elinvar for making hairsprings and balance wheels. Its coefficient of expansion is so low that no compound bar is needed. It seems to be superior to bimetals for use in balance wheels. It does not corrode easily and it does not become permanently magnetized. The elasticity of this alloy remains practically constant under temperature changes. (See Fig. 316.)

**255. How is a pendulum compensated for temperature changes?** From our study of the pendulum, we know that a long pendulum vibrates more slowly than a short one. For that reason, the rod that supports the pendulum bob of an inexpensive clock contracts in winter and the clock gains time. As it expands in summer the clock loses time. Invar is a metal used for the pendulum rods of some clocks, but *very accurate* clocks have compensated pendulums. Two types are in use:

1. *Mercury type.* The length of a pendulum is measured from the point of suspension to the center of oscillation. The lengthening of the rod of the mercury pendulum shown in Fig. 317*A* lowers the center of oscillation and tends to slow down the vibration rate. But the mercury at the same time expands upward and raises the center of oscillation by exactly the same amount that it was lowered by the expansion of the rod. Such a pendulum keeps accurate time, since temperature changes do not affect it.

2. *Compensating rod type.* In the pendulum of Fig. 317*B* the light-colored rods are of brass and the dark-colored rods are of steel. The brass rods are slightly shorter than the steel, but brass has a greater coefficient of expansion. You will observe that the expansion of the steel rods tends to increase the length of the pendulum since they expand downward. But the expansion of the brass rods tends to raise the center of oscillation, since such expansion is upward. If the rods are of the correct proportional lengths, the expansion of one set of rods nullifies the effect of the expansion of the other set of rods.

**256. Do liquids expand when heated?** If one fills a tank with gasoline on a cool evening, and then lets it stand in the sun the next day, some of the gasoline will overflow. Heat causes liquids to expand. We have already had examples of the expansion of mercury

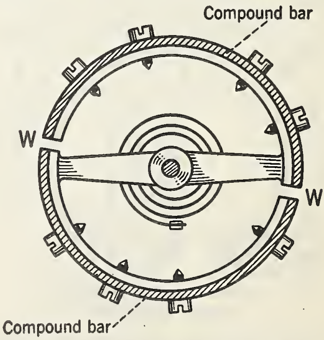
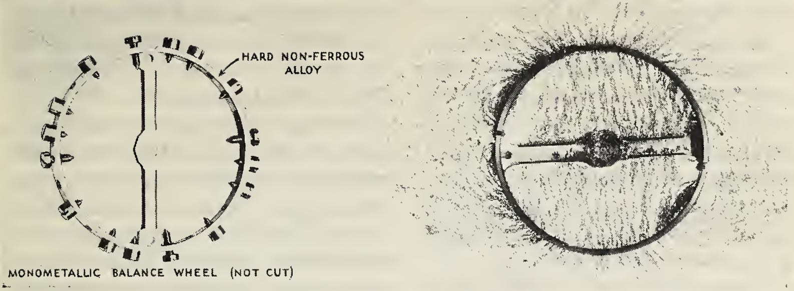


FIG. 315. A compensated balance wheel.


HARD NON-FERROUS ALLOY
MONOMETALLIC BALANCE WHEEL (NOT CUT)

*Courtesy of the Hamilton Watch Company*

FIG. 316. The elinvar balance wheel (left) is not magnetic.

and alcohol in thermometers. When the housewife cans fruit, or bottles grape juice, she fills the container full of the hot juices. Then the container is sealed. When it has cooled to room temperature, the liquid contracts until it no longer fills the container.

An apparatus similar to that shown in Fig. 318 is used to measure the coefficient of expansion of liquids. With liquids, we are not concerned with anything but their increase in volume. We measure their coefficient of *cubical* expansion, which is approximately *three times the coefficient of linear expansion.*

Liquids have a higher coefficient of expansion than solids. This is obvious when we compare the expansion of mercury in a thermometer with the expansion of the glass. The amount of expansion of liquids varies considerably with the temperature, but the expansion of mercury is fairly uniform between 0° C. and 100° C. Otherwise the

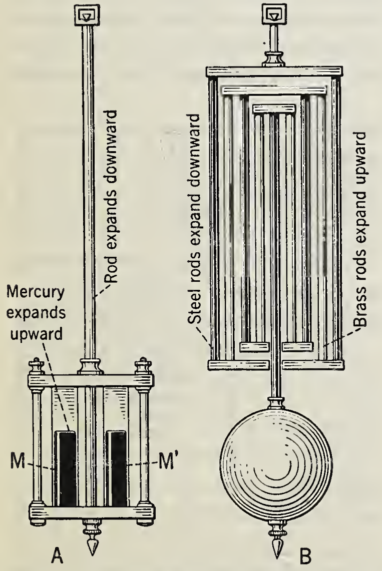

Rod expands downward
Mercury expands upward
M
M'
A
Steel rods expand downward
Brass rods expand upward
B

FIG. 317. Two types of compensated pendulums. *A*. Mercury. *B*. Bars of iron and brass.

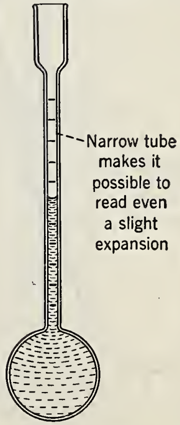

Narrow tube makes it possible to read even a slight expansion

FIG. 318. Tube to measure liquid expansion.

degrees on a thermometer would be unequally spaced.

The coefficient of cubical expansion of mercury is 0.00018, nearly seven times that of glass; of water, from 5° C. to 8° C., 0.00002; of water, 99° C. to 100° C., 0.00076; of alcohol, 0.0011; and of petroleum, 0.0009.

Problem. 100 gallons of petroleum are measured at 0° C. What will be the volume of the petroleum at 30° C.?

*Solution.* 0.0009 × 30 = 0.027 gal., the expansion of 1 gallon when heated 30 degrees. 0.027 × 100 = 2.7 gals., total expansion. 100 + 2.7 = 102.7 gals., the new volume.

**257. What is peculiar about the expansion of water?** If we fill a bottle like that of Fig. 318 with water at 100° C., we shall find that it gradually contracts as it cools until a *temperature of* 4° *C. is reached.* Then it will expand again as we cool it on down to the freezing point, 0° C. Of course, when a substance contracts, its density is increased, because its mass is always constant. Therefore, *water has its greatest specific weight, which is 1.00000, at a temperature of* 4° *C.* At 0° C. its specific weight is 0.99987; at 20° C., its specific weight is 0.99825. See Table 11 in Appendix B.

We can find the *specific volume* of a body by dividing *one* by its specific weight. In the metric system the specific volume is that particular volume of the body in cubic centimeters that is needed to weigh one gram. The *unusual* way in which water expands when heated or contracts upon cooling is clearly shown by a curve like that of Fig. 319. In this graph, the specific volumes of water are used as ordinates and the temperatures as abscissas.

If water continued to contract upon cooling until the freezing point were reached and did not expand upon freezing, ice would sink to the bottom of a pond or stream. During a long, cold winter such formation of ice would continue until the pond or stream was frozen solid. If the ice were at the bottom, it would thaw only a few feet in summer. Fish and other

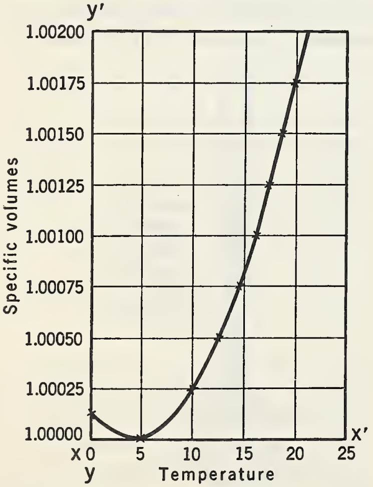
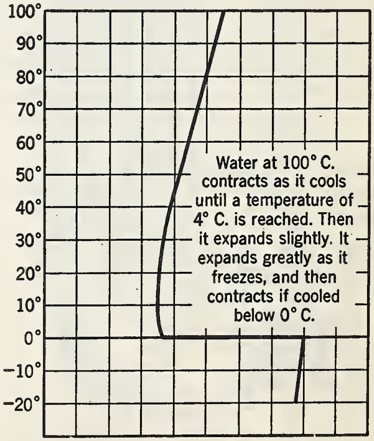


Fig. 319. Expansion curve of water.



Water at 100° C. contracts as it cools until a temperature of 4° C. is reached. Then it expands slightly. It expands greatly as it freezes, and then contracts if cooled below 0° C.

Fig. 320. Curve to show how water contracts when cooled.

forms of aquatic life would perish, and many streams in the temperate zones would be closed to navigation. As it is, no ice is formed at the surface until all the water in the pond is cooled to 4° C. The water at the bottom of a frozen pond is always 4° C., whether the temperature above the ice is 20° C. or − 40° C.

Let us refer to Fig. 320. The graph in this figure shows how a given volume of water *contracts* upon cooling from 100° C. to 4° C., *expands* upon cooling from 4° C. to 0° C., *expands* sharply upon freezing, and then *contracts* again when the ice is cooled below 0° C.

**258. Do gases expand when heated?** When bread or biscuit dough is put in the oven, the gas used for leavening expands greatly during the heating. This expansion makes the dough rise. Experiment shows that all gases expand when heated. Unlike solids and liquids, *all gases have the same coefficient of expansion*, and *it is uniform at all temperatures*. With gases we are concerned *only* with the cubical coefficient of expansion, or their increase in volume. The value of the coefficient of cubical expansion for all gases is $\frac{1}{273}$ of the volume at 0° C., or 0.003665 per degree Centigrade. It is about 20 times as great as that of mercury and almost 60 times that of aluminum.

**259. How is the coefficient of expansion of gases measured?** In 1787, Charles, a Frenchman, performed experiments proving that all gases expand the same amount when heated one degree, if the pressure is kept constant. Let us take a small glass tube, sealed at one end, and measure the air column inclosed by a globule of mercury $M$, as shown in Fig. 321, when the tube is immersed in ice water. Next we may measure the length of the air column when the tube is immersed in steam. We find that the air column has increased in length $\frac{100}{273}$ of its original length, when heated from 0° C. to 100° C. For each degree of temperature change, the expansion is $\frac{1}{273}$ of the volume at 0° C. When other gases are used, the same result is obtained. While Charles was the first to study the expansion of gases, the law sometimes bears the name of Gay-Lussac, who was the first to announce the law showing the relation of the volumes of gases to their temperatures.

**260. How does expansion affect density?** Heating a gas, a liquid, or a solid does not change its weight. But if its volume is increased by heating, then its density must be reduced. For this reason, we find that the warmer, lighter air of a room is near the ceiling. Hot water accumulates at the top of the tank. When we study the methods of distributing heat from one place to another, we shall find that the fact that gases and liquids are less dense when hot than they are when cold plays an important role.

When a confined gas is heated so that

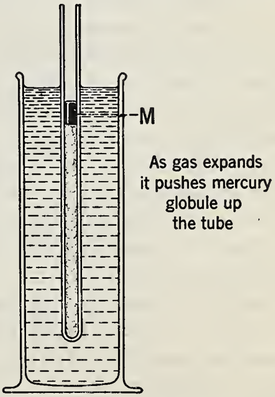


Fig. 321. Tube to measure the coefficient of expansion of gases.

it cannot expand, the pressure which the gas exerts is increased. A balloon tire pumped up on a cool morning may show a gauge pressure of 35 lb. per sq. in. If the tire stands in the sun so that the temperature of the air inside is increased 20 or 30 degrees Centigrade, it may show a pressure of 38 or 39 lb. per sq. in. Raising the temperature increases the velocity of the molecules, and they bombard the inner walls of the tire more vigorously, thus increasing the pressure.

**261. What is meant by absolute temperature?** Since gases contract when cooled, it is interesting to inquire what will happen as we continue to cool them below 0° C. Let us start with *unit* volume at 0° C. But unit volume is really $\frac{273}{273}$. For every degree we cool the gas below zero, its volume will be decreased $\frac{1}{273}$. At − 100° C. it is decreased by $\frac{100}{273}$, and only $\frac{173}{273}$ of its original volume will be left. At − 200° C., only $\frac{73}{273}$ will be left. How much will remain if we cool the gas to − 273° C.? Theoretically, it will have *lost all its volume.* At *zero volume* all molecular motion would cease and the body would be without any heat, or *absolutely* cold. For this reason, − 273° C. is taken as zero on the *absolute temperature scale* devised by Lord Kelvin. Thermometers are never graduated on the absolute scale and it is not used for measuring temperatures. It is merely an arbitrary scale which was devised to eliminate the *zero* and the *minus* from regular thermometer scales when comparing gas volumes.

In reality, all gases liquefy before absolute zero is reached. One scientist after another has attempted to cool some gas to absolute zero. One of the best known cryogenic laboratories is at Leyden, Holland, where Kamerlingh Onnes liquefied helium in 1908. De Haas, working in this laboratory, succeeded in reaching a temperature within 0.003 of a Centigrade degree of Absolute zero. The table given below shows the relation between the Absolute and Centigrade scales, and the relation of the Absolute scale to the volume of a gas which measures 273 c.c. at 0° C.

| CENTIGRADE | ABSOLUTE | VOLUME |
|---|---|---|
| 100° | 373° | 373 c.c. |
| 50° | 323° | 323 c.c. |
| 0° | 273° | 273 c.c. |
| −100° | 173° | 173 c.c. |
| −273° | 0° | 0 c.c. |

By comparing columns one and two we see that the absolute temperature is exactly 273 degrees higher than the Centigrade temperature. Hence, to change from Centigrade to Absolute scale, we add 273 degrees to the Centigrade reading. The third column shows how 273 c.c. of gas at standard temperature, 0° C., would behave if subjected to the temperatures shown in the other columns. At 100° C., or 373° A., its volume is 373 c.c.; at − 100° C., or 173° A., its volume is 173 c.c. From these observations, it is apparent that the LAW OF CHARLES may be stated as follows: *If the pressure be constant, the volume of a given mass of dry gas is directly proportional to the absolute temperature.*

PROBLEM. At a temperature of − 23° C., the volume of a gas measures 1000 c.c. Find its volume at a temperature of 27° C.

*Solution.* − 23° C. = 250° A., and 27° C. = 300° A. The gas has been warmed; hence it will expand to $\frac{300}{250}$ of its former volume. $\frac{300}{250} \times 1000 = 1200$ c.c., the new volume.

**★262. The law of Charles can be shown graphically.** Let us use the absolute temperatures and volumes given in Section 261 as co-ordinates in plotting a curve. The curve obtained is shown in Fig. 322. It is a simple direct proportion curve, and it shows graphically that the volume of a gas is directly proportional to the *absolute* temperature.

If we plot a curve by using the volumes as abscissas and the *Centigrade* temperatures as ordinates, as shown in the same table, we see that the volumes are *not* proportional to the Centigrade temperatures at all. If we produce the curve $AB$ until it intersects the $YY'$ axis at $Z$, we find that this point of intersection corresponds to − 273° C., or to zero degrees Absolute. This furnishes us with a graphic illustration of the *theoretical* temperature at which all gases cease to have volume. In the similar triangles, $ZCD$ and $ZOA$, the volumes, as represented by $OA$ and $CD$, are proportional to the *absolute* temperatures, $OZ$ and $CZ$. (See Fig. 323.)

There is no simple volume relationship corresponding to 0° C. and 10° C., or to − 10° C. and 10° C. The latter two, if used in proportion, would give a negative volume, which is impossible. The Absolute scale eliminates the zero and negative temperatures of the Centigrade scale.

Absolute temperature, $T$, = Centigrade temperature, $t$, + 273. Or, $T = t + 273$.

**263. Here are some problems involving the use of the law of Charles.** Given 400 c.c. of gas measured at 10° C.; suppose we wish to find what volume the gas will occupy at 60° C. We must first reduce the Centigrade temperatures to absolute. 10° C. = 283° A. and 60° C. = 333° A. Let $V$ represent the original volume; $V'$, the new volume; $T$, the original temperature; and $T'$, the new temperature.

Then by the law of Charles,

$$V : V' = T : T'.$$

Substituting, $400 : x = 283 : 333$.

Whence, $x = 470.6$ c.c.

It is quite as simple to solve by fractions. The temperature has increased and the volume will be correspondingly increased. Hence the new volume is $\frac{333}{283}$ of the original volume. $\frac{333}{283} \times 400 = 470.6$ c.c.

**264. Here are some problems involving the use of the laws of Boyle and Charles.** It frequently happens that

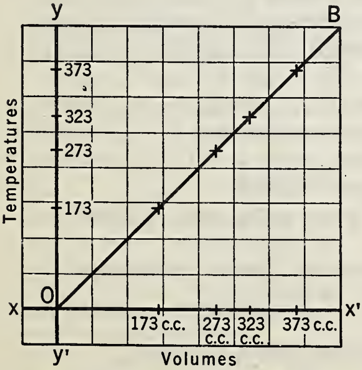


Fig. 322. Direct proportion curve to represent the Law of Charles.

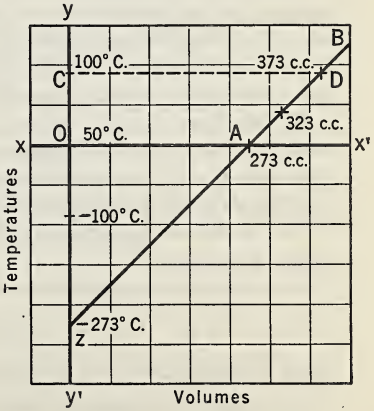


Fig. 323. Curve to show absolute zero.

both the temperature and pressure to which a given volume of gas is subjected may change. To find the new volume in such a case, we must use the laws of Charles and Boyle. We may find the effect of the pressure on the volume and then use this new volume in order to find the effect of temperature. Or we may find the effect of both by the use of a single statement.

Problem. Given 500 c.c. of gas at 20° C. and 750 mm. pressure; find what volume the gas will occupy at 30° C. and 760 mm. pressure.

*Solution.*

20° C. = 293° A.; 30° C. = 303° A.

Then, $500 \times \frac{303}{293}$ = the volume corrected for temperature change only.

And, $500 \times \frac{750}{760}$ = the volume corrected for pressure change only.

Since both the temperature change and the pressure change occur simultaneously, we may combine the equations as follows:

$$500 \times \frac{303}{293} \times \frac{750}{760} = \text{corrected volume.}$$

Note. The increase in temperature from 20° C. to 30° C. causes the gas to expand by $\frac{303}{293}$ of its volume, and the increase in pressure reduces the volume by $\frac{750}{760}$.

The following formula may be used for solving problems when both the absolute temperature and pressure change: $\frac{PV}{T} = \frac{P'V'}{T'}$. In this formula, $P$, $V$, and $T$ represent the original pressure, volume, and absolute temperature respectively; $P'$, $V'$, and $T'$ represent the new pressure, volume, and absolute temperature.

**265. How great is the force of expansion?** The force of expansion or contraction is enormous. Broken wires in winter, cracks in pavements, and the bursting of tires when highly heated all testify to the great force exerted by a change in temperature. Concrete walks buckle under the force of expansion. The magnitude of this force seems to be limited only by the breaking strength of the material at the given temperature. With a steel bar of 1 sq. in. cross-sectional area, the force may be nearly 70 tons.

## Summary

In general, solids expand when heated and contract when cooled. The increase per unit length per unit degree is called the coefficient of linear expansion. The increase in area, or the coefficient of superficial expansion, is approximately twice the linear coefficient. The increase in volume, or the coefficient of cubical expansion, is three times the linear coefficient.

Liquids have a much higher coefficient of expansion than solids; alcohol expands nearly 30 times as much as steel, and mercury nearly 5 times as much. Water has its maximum density at 4° C.; heated above this temperature or cooled below it, water expands.

The coefficient of expansion of all gases is the same, 0.003665 per degree Centigrade.

A change in temperature or a change in pressure will change the volume of a gas. The GAS LAW, $\frac{VP}{T} = \frac{V'P'}{T'}$, is used to calculate the effect of temperature and pressure changes upon gas volumes.

*How many of the following terms can you define or explain? (A type of self-mastery test.)*

Coefficient of expansion
Effect of unequal heating
Pyrex glass
Compensated pendulum
Expansion of gases
Expansion and density
Thermostat
Compound bar
Peculiar expansion of water
Law of Charles
Absolute temperature
Radiator valves

## QUESTIONS

1. How would thermometer readings be affected if mercury and glass had the same coefficient of expansion?

2. When two tumblers stick together they may usually be loosened by pouring cold water into the inner one, or by letting hot water run over the outer one. Explain.

3. Why must all the water in a pond be cooled to 4° C. before any of it freezes?

4. Why do ponds and lakes freeze around the edges before they do in the middle?

5. Fused silica has a coefficient of expansion of about 0.0000005. Explain why it is superior to glass for laboratory apparatus that is to be heated.

6. Why is glassware to be heated in the laboratory made of thin glass instead of thick glass?

7. Sometimes a housewife instructs her maid never to pour hot water into her thin glass tumblers. Is she really scientific?

8. A football is inflated in a warm room. It is used out-of-doors on a cold day. Will it grow looser or tighter? Explain.

9. Why is invar used in making clock pendulums, and the tapes used by surveyors?

10. Compare the coefficients of linear expansion of "Pyrex" glass and ordinary glass. Explain why dealers in "Pyrex" glass can guarantee to replace baking dishes made of "Pyrex" if they break when being heated.

11. Are high or low temperatures generally associated with high-barometer areas? Explain.

12. How does the law of Charles apply in the baking of bread?

13. Rivets used to hold together steel plates in construction work are heated red hot before they are headed. Why?

14. Why are concrete roads marked off into blocks, and the cracks filled with tar or bitumen when building roads?

15. Would a single large sheet of copper be satisfactory to cover one half of a roof on a house? Explain.

16. Metal straps are used to support the steampipes in the basement. Explain why this method is used.

17. One hot summer's day one of the drawbridges across the Passaic River could not be closed. Can you give a reason and suggest a remedy?

18. Why is it impossible to seal a brass wire into a glass rod?

19. Why is it harder for a plumber to make a tight joint with a brass hot-water pipe than with one of galvanized iron?

20. Is it better economy to have your gas meter in the basement or in the attic? What two factors must be taken into consideration in answering the foregoing question?

21. How would natural conditions be affected if water continued to contract until it froze?

22. When some of the gasoline pumps had ten-gallon glass cylinders at the top for storage, a certain motorist would never stop for gasoline at a station unless it stood in the shade. Explain.

23. A small rubber balloon filled with hot air rises. Explain.

24. The air above the ice of a pond is − 10° C. What temperature would you expect the upper surface of the ice to have? The lower surface? The water just beneath the surface? The water at the bottom of the pond?

25. Why does the air escaping from the valve of a pneumatic tire feel cool, even in hot weather?

26. Glass stoppers are sometimes difficult to remove from bottles. Why does pouring hot water over the neck of the bottle help to loosen them?

27. An automobile owner neglects to oil his car. What does a mechanic mean when he speaks of a moving part as having "frozen"?

28. Why are large piles of broken rock usually found at the base of rocky cliffs?

29. What are the properties of elinvar which make it useful?

## PROBLEMS

### Group A

1. A steampipe is 40 ft. long at a temperature of 10° C. How much does it expand when steam at 100° C. is passed through it? What is its new length?

2. An aluminum wire is 3000 ft. long at 0° C. What is its length at 150° C.?

3. A wire is 100 cm. long at 20° C. At 80° C., it is 100.1104 cm. long. What is its coefficient of linear expansion?

4. At − 20° C. the steel cables of the George Washington Bridge are 8700 ft. long. How much will they increase in length if heated to 40° C.?

5. A brass rod is 60 ft. long at 0° C. To what temperature must it be heated to increase its length to 60.324 ft.?

6. A man buys 200 gallons of alcohol when the temperature is 0° C. He lets the unstoppered cans stand in a room which is 30° C. If they were full in the beginning, how much alcohol will overflow?

7. A gas measures 500 c.c. at a temperature of 13° C. Find its volume when the temperature is 25° C.

8. A 1000-gallon tank is filled with gasoline at a temperature of 0° C. How much will overflow when the temperature rises to 25° C.?

9. A gas measures 3 quarts at 0° C. To what temperature must it be cooled to reduce its volume to 2 quarts?

10. Given 900 c.c. of gas measured at S.T.P. (0° C. and 76 cm. pressure). Find its volume at 27° C. and 78 cm. pressure.

### Group B

11. Steel rails that are laid when the temperature is 20° C. measure 34 ft. If the maximum temperature is 122° F., how much space should be left between the rails?

12. A surveyor's tape is made of invar. It is 100 ft. long when the temperature is 0° C. If this tape is used to measure a plot 4000 ft. long when the temperature is 104° F., how much will the measurement be in error?

13. A gas measures 1500 c.c. at 47° C. and under a pressure of 80 cm. Find its volume at S.T.P.

14. A gas measures 400 c.c. at a temperature of 27° C. and a pressure of 900 mm. To what temperature must the gas be cooled to reduce its volume to 300 c.c. when the pressure is 600 mm.?

15. A tire is inflated to a gauge pressure of 30.3 lb. when the temperature is 7° C. What will be the pressure inside the tire when the air inside is heated up to a temperature of 37° C.? What will the gauge read?

16. A room is heated from 0° C. to 30° C. What fractional part of the air escapes? If the density of the air in the beginning was 0.00128 gm. per c.c., what will its density be at 30° C.?

17. Reduce to S.T.P. the following: 2100 c.c. of gas at 17° C. and 3 atmospheres pressure.

18. Reduce to S.T.P. the following: 100 cu. ft. of gas measured at 116.6° F. and 100 in. of mercury.

19. Reduce to S.T.P.: 400 c.c. of gas at 86° F. and 86 cm. pressure.

# *Heat Units — Change of State*

## 1. Heat Units — Specific Heat

**266. How is heat measured?** We use thermometers to measure temperatures, but they cannot be used to measure heat. We have learned, too, that two substances may have the same temperature, but different quantities of heat. When a man buys coal, he is interested to know how many *heat units* he has bought, and not how high a temperature the burning coal will produce. It is possible to measure in the laboratory the *heat content of a weighed sample of fuel by finding the effect which it can produce.* If we find, for example, that one sample of coal will heat one liter of water *one* degree, and that another sample of coal will heat one liter of water *two* degrees, then we know that the heat content of the latter is just double that of the former. Once again, we shall use pure water *as a standard* in the definition of heat units.

**267. What heat units are used?** 1. *The calorie.* We talk a great deal about *calories,* and the number that we eat each day. The term is so loosely used that it may mean to one person "boiled rice," to another "ice cream," and to a third "fat bacon." What does it mean to a physicist? *The calorie is defined as the quantity of heat needed to warm one gram of water through one degree Centigrade.* When one gram of water cools through one degree Centigrade, *it loses one calorie of heat.* To warm one gram of water ten degrees one would need ten calories, and it would also take ten calories to raise the temperature of ten grams of water one degree Centigrade. One gram of a good grade of soft coal gives out about 8000 calories as it burns.

What does the calorie mean to the biologist? In the study of biology and in dietetics the *large Calorie* is used. We shall spell it with a capital *C* to avoid confusion. The large Calorie is equal to 1000 small calories. It is the amount of heat needed to raise the temperature of 1000 grams, or 1 kgm. of water, 1° C. When we say, "A thick slice of bread furnishes 100 Calories," we mean that the bread, if totally ox-

---

### Vocabulary

| | |
|---|---|
| DIETETICS | hygienic science relating to diet. |
| FUSION | melting. |
| VAPORIZATION | changing from a liquid to a vapor. |
| SUBLIMATION | changing from a solid to a vapor without melting. |
| SULFUR DIOXIDE | a gas formed by burning sulfur. |
| REGELATION | melting under pressure and freezing again as pressure is reduced. |
| DISTILLATION | a process of vaporization and condensation. |
| WELDING | pressing or hammering two metal bars into permanent union. |
| PLASTIC | capable of being molded, pressed, or hammered into a desired shape. |

idized, would supply the body with enough heat to raise the temperature of 1000 gm. of water 100° C. Or, it would raise the temperature of 100,000 gm. (100 kgm.) 1° C. The Calorie is a measure of the fuel value of the food.

2. *British thermal unit.* The heat unit used in the English system is the *British thermal unit* (*B.T.U.* or *Btu.*), which is the *amount of heat required to raise the temperature of 1 lb. of water 1° F.* One pound of coal furnishes from 9000 to 16,000 *B.T.U.* One cu. ft. of artificial fuel gas furnishes from 500 to 625 British thermal units when it burns. Natural gas may furnish 1000 or more *B.T.U.*'s per cu. ft. *One B.T.U. equals 252 small calories.*

**268. Substances vary in heat capacity.** Let us perform the following experiment, which was devised by Tyndall, a famous English scientist: We have five metal balls, aluminum, iron, copper, zinc, and lead, and a five-pronged support. The balls are first placed in a flat-bottomed pan of boiling water to heat them all to the same temperature. Then they are placed upon a thin sheet of paraffin. The aluminum melts its way through the paraffin rapidly, followed by the iron. Although the aluminum ball is lighter, yet it absorbed more heat. The copper and zinc follow at almost the same rate, while the lead melts the paraffin slowly. If all the balls have the same weight, we find that the aluminum absorbs the most heat in the boiling water, and it then gives up more heat to the paraffin. We also conclude that of the five metals lead has the lowest capacity for absorbing heat. We conclude that some substances heat slowly and cool slowly because they have a high *heat capacity*, absorbing more calories while being warmed, and liberating more calories upon cooling. *The heat capacity of a body may be defined as the amount of heat needed to raise its temperature 1° C.*

**269. What is specific heat?** Water heats slowly and cools slowly. It has the highest heat capacity of any ordinary substance. From the definition of the calorie, we conclude that the *heat capacity of water is one.* Since the word "specific" implies a ratio, then the *specific heat of a substance is the ratio of its heat capacity to that of water.*

We may define specific heat in terms of the heat units. For example, the *specific heat of a substance is equal to the number of calories needed to raise the temperature of 1 gm. of the substance 1° C.* In the English system, it is the number of *B.T.U.*'s required to raise the temperature of 1 lb. of the substance 1° F. *The specific heat of water is one.*

By experiment, it is possible to show that a given weight of iron when heated rises in temperature about 9 times as fast as the same weight of water. Hence we conclude that its specific heat is only about $\frac{1}{9}$ as much as that of water. The average of a large number of trials shows that it takes only 0.113 calorie to warm one gram of iron 1° C. Hence, the specific heat (sp. ht.) of iron is 0.113. From Table 6, Appendix B, we see that the specific heat of most substances is rather small when compared to that of water.

What facts can we infer from simple arithmetic? If 1 calorie warms 1 gm. of water 1° C., then 100 calories will warm 100 gm. of water 1° C., or 100 calories will warm 1 gm. of water 100° C. In all cases of this kind, it follows that: *weight (in gm.) × change of temperature (C) × sp. ht. = calories.* or, *weight (in lb.) × change in temperature (F) × sp. ht. = B.T.U's.*

To illustrate: we find the number of calories needed to raise the temperature of 300 gm. of iron through 50° C. by multiplying its weight (300 gm.) by its change in temperature (50° C.) by its specific heat (0.113). Or, suppose that we wish to find the number of calories that 200 gm. of water will liberate in cooling from 80° C. to 20° C. Calories = weight (200 gm.) × temperature change (80° C. – 20° C.) × specific heat (1).

**270. What is the law of heat exchange?** If our coffee is too hot, we may cool it by adding to it some cold water. Thus the coffee is cooled, but the water which we added is warmed, and the final temperature of the mixture will be some point between the two initial temperatures. If we touch a hot metal pan, our hand *gains* heat. If we touch a block of ice, our hand *loses* heat. Whenever we bring into contact two substances of *unequal* temperature, or mix them thoroughly, we find that *the warmer one loses heat* and that *the cooler one gains heat,* until both finally reach the *same* temperature. It is customary to say that heat flows from the warmer substance to the colder one. Prevost showed that in all such cases, *the total number of heat units lost by the warmer substance equals the total number of heat units gained by the cooler substance.* We shall find this statement, known as the LAW OF HEAT EXCHANGE, most useful in solving problems involving an exchange of heat.

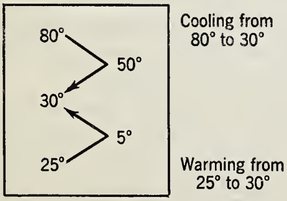


FIG. 324. Both substances reach the same final temperature.

In a laboratory experiment, 100 gm. of iron at 80° C. were added to 113 gm. of water at 25° C. The final temperature of the mixture was found to be 30° C. From Fig. 324, in which the temperatures are all given, we see that the iron has cooled through 50° C., from 80° C. down to 30° C. We note that the water was warmed from 25° C. to 30° C., a change in temperature of 5° C. Then, 100 gm. (wt. of iron) × 50 (change in temp.) × 0.113 (sp. ht. of iron) = 565, the number of calories lost by the iron. And, 113 gm. (wt. of water) × 5 (temp. change of water) × 1 (sp. ht. of water) = 565 calories, gained by water. If any one of the six quantities is unknown it may be found from the equation,

*Calories lost = calories gained.*

**★271. How can specific heat be measured?** The method of mixtures is generally used for finding the specific heat of a substance. Suppose that we have a lump of brass of which we wish to find the specific heat. We weigh a calorimeter, or metal cup, of known specific heat. Then some cold water is added to the calorimeter and the com-

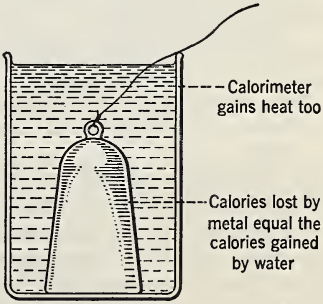

Calorimeter gains heat too
Calories lost by metal equal the calories gained by water

FIG. 325. Metal loses heat and water gains heat.

bined weight of calorimeter and water is found. The lump of brass is then weighed and suspended in steam arising from boiling water. Probably the temperature is 100° C. Next the cold water is stirred with a thermometer and its temperature is taken. Then the brass is quickly transferred to the cold water. Of course there is some loss of heat while such transfer is being made. (See Fig. 325.) The water is stirred with the thermometer until the mercury stops rising. The temperature at which this occurs is the final temperature of the mixture. The brass has been cooled, and the water and the calorimeter have been warmed. Let us assume the following data:

| | |
|---|---|
| Weight of calorimeter........ | 110 gm. |
| Specific heat of calorimeter... | 0.09 |
| Weight of water............. | 405 gm. |
| Weight of brass............. | 201.9 gm. |
| Initial temperature of the water.................... | 20° C. |
| Initial temperature of brass... | 100° C. |
| Final temperature of water and brass.................... | 23.5° C. |

The brass loses heat as follows:

Weight (gm.) × change of temperature × specific heat = calories. Or, $201.9 \times (100–23.5) \times x =$ calories.

The water and the calorimeter gain heat as follows:

$110 \times (23.5 - 20) \times 0.09 = 34.65$ calories, gained by calorimeter.

$405 \times (23.5 - 20) \times 1.00 = 1417.5$ calories, gained by water.

Total calories gained = 1452.2.

By Prevost's theory, *heat lost equals heat gained.*

Then, $201.9(76.5)\,x = 1452.2$ calories.

Whence, $x = 0.094$, the specific heat of brass.

This method is a general one. In all problems involving heat exchange and specific heat, the student needs to consider *which substances lose heat and which gain heat;* he should bear in mind the fact *that calories gained equal calories lost;* and he must remember *that weight in grams times change in temperature in degrees Centigrade times specific heat equals calories.*

**272. How does high specific heat of water affect us?** On one of those rare days in early June, the air in the latitude of New York may seem quite warm. If we are rash enough to take a dip in some lake, we find the water decidedly cold. The water warms much more slowly than the land. In October, the reverse is true. The air may be chilly, but the water will feel quite warm. Water cools slowly. It takes quite a long time to heat a quart of water to its boiling point. In a hot-water bottle in the sick room a couple of quarts of water will remain warm almost all night.

Along the Great Lakes regions we find a fruit-growing belt. The area warms up more slowly in the spring and the fruit trees do not bloom early enough to be nipped by late frosts. In the fall the water retains the heat and early frosts are not likely to destroy the fruit before it matures.

Cities situated on large bodies of water are not subject to so great extremes of temperature as inland cities. There is not much difference in Latitude between San Francisco and St. Louis. But San Francisco, tempered by the Pacific Ocean, has a more equable climate than St. Louis. New York City is on the ocean, but its climate is subject to greater extremes than that of San Francisco because it is affected by the westerly winds which blow across the continent.

One of the coldest spots on the earth is Northern Siberia. It is far distant from any large body of water except the Arctic Ocean, and that ocean cannot moderate its climate to any marked degree.

## 2. Fusion

**273. What is fusion?** When a solid is warmed, it absorbs heat. At a certain temperature, it changes from the solid to the liquid state. *The process of changing from the solid to the liquid state is called fusion.* It is also known as *melting*, or *liquefaction*. The temperature at which such a change occurs is called the *melting point*. *Pure* substances generally have a *definite* melting point, and different solids have different melting points. The determination of the melting point of a solid is often used as a test for its purity.

When a liquid changes from a liquid to a solid state, the process is called *solidification*. We have already learned that some of the solids formed in this way crystallize in regular geometric forms. The temperature at which solidification begins is known as the *freezing point*. For crystalline substances the melting point and the freezing point have the same temperature.

*Non-crystalline* substances like glass and sealing wax have no definite melting point, but they soften gradually when heated. Such substances may be heated until they soften and then be bent, molded, or welded. Wrought iron becomes plastic when it is heated. The blacksmith heats two pieces of wrought iron until they begin to soften, and then pounds them together into a single piece by a process known as *welding*. Cast iron has a sharp melting point, and it cannot be welded in this manner. It has been said that we live in an age of plastics. One wonders what the civilized world would do without such plastics as clay, glass, celluloid, pyralin, cellophane, bakelite, rubber, etc.

The tensile strength of a substance is reduced as its temperature rises. Structural material, such as steel, may collapse during a fire as a result of such weakening, even before the melting point is reached. In some cases, this seems to be the reason for the collapse during a fire of so-called fireproof buildings.

**274. How does the volume change upon solidification?** When molten paraffin is poured into a tumbler and permitted to solidify, the center will be found depressed, as in Fig. 326. Paraffin contracts when it solidifies. Many metals and alloys behave in the same manner. In fact, *non-crystalline* substances tend to *contract* upon solidification.

In winter, we find water pitchers broken by the force of expansion of the water as it freezes. On cold mornings, we see milk bottles, with the frozen milk extending up above the neck of the bottle. Water pipes may burst if the water in them freezes, and automobile radiators that have cracked from the expansive force which water exerts upon solidifying are too common. The volume occupied by ice is about 1.1 times that occupied by the water from which the ice was formed. The force of expansion is enormous.

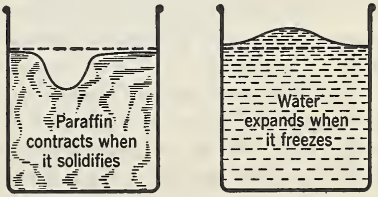

Paraffin contracts when it solidifies
Water expands when it freezes

Fig. 326. Some liquids expand upon freezing, others contract.

We find that rocks are split by the expansive force exerted when water flows into crevices and then freezes. There is an erroneous idea common in some localities that water pipes do not burst when they freeze, but that they burst when the pipes are thawed out. Of course the pipes do not show a leak until the ice inside has melted.

Bismuth and antimony expand upon solidification. Antimony is a constituent of type metal. Because it expands when the molten metal is poured into a mold, the type will be sharp and clear-cut. We find that many *crystalline* substances *expand* when they change from the liquid to the solid state.

**275. How does the expansion of water upon freezing help us?** Naturally, we are not pleased to have water expand and burst our water pipes and milk bottles. But let us inquire what would happen if water contracted upon solidifying. Ice would be denser than water. The first layer of ice formed at the surface of a lake would sink. Other layers would sink as soon as formed until the entire body of water would be frozen solid in winter. The Great Lakes, as well as other lakes and streams in the middle latitudes would be frozen solid throughout.

The sun's heat rays do not penetrate water to any considerable depth. The lakes would not thaw out even in summer, except to a slight depth. Fish and all forms of aquatic life would perish in the Temperate Zones, and our lakes and streams would be closed to navigation.

**276. How does pressure affect the melting point?** When snow is soft, it will "pack." When we make a snowball, the snow at the surface melts under the pressure which we apply. It freezes again as soon as we release the pressure, and the shell of ice thus formed holds the snowball together. Such behavior is characteristic of solids that *expand* upon freezing. Their *melting point is lowered by pressure.*

Let us suspend two weights by means of a strong wire over the surface of a cake of ice, as in Fig. 327. The pressure directly beneath the wire lowers the melting point of the ice, and the weights pull the wire into the ice. As the pressure is then released, the water above the wire freezes again. Thus the wire will cut its way through the ice, but the block will still be solid ice after the wire has passed entirely through the cake. Such *melting under pressure and freezing again after the pressure is released is called regelation* (*re*, again + *gelatio*, a freezing). Much of the movement of valley glaciers is due to regelation.

A very great pressure is needed to lower the melting point of ice a great deal. For example, a pressure of one atmosphere reduces the melting point only 0.0075° C. If snow is very much colder than 0° C., it will not "pack" readily.

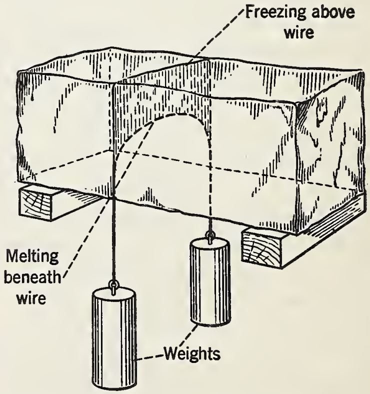


Fig. 327. Pressure lowers the melting point. The freezing again of the water is regelation.

If we increase the pressure on a substance such as paraffin, which contracts when it solidifies, its melting point is increased. The student will note that the behavior of such substances is just the opposite of that of substances which expand when they freeze. Some rocks in the interior of the earth are probably hot enough to melt at normal pressure, but they remain solid because they are under stupendous pressure. If the pressure is released, they melt and form the lava of volcanoes.

**277. How much heat is needed to melt one gram of ice?** Let us put a pan of ice water containing a few lumps of ice on a gas burner and stir the mixture all the time the ice is being melted. The temperature is 0° C. when we begin and it does not rise above 0° C. until all the ice is melted. Heat is certainly being absorbed, but since the temperature does not increase, it is evident that the heat is being used merely *to melt the ice. The number of calories needed to melt one gram of a substance without increasing its temperature is called its heat of fusion.* At one time it was known as *latent* (hidden) heat, because a thermometer does not show any evidence of its presence. The average of a large number of carefully performed experiments shows that it requires approximately 80 calories of heat to convert 1 gm. of ice at 0° C. into 1 gm. of water at 0° C. In melting, ice takes heat from the substances around it, thus lowering their temperature. Because ice has so high a heat of fusion, it makes an excellent refrigerating agent. It requires 144 B.T.U. to change 1 lb. of ice at 32° F. into water at 32° F.

In the heat of fusion, we have an example of the effect of heat in producing a change of state. Fig. 328 shows what happens when we *add* heat to a solid. If we *subtract* enough heat from a liquid, it will solidify. To convert 1 gm. of ice water at 0° C. into ice at 0° C., one must *subtract* 80 calories of heat.

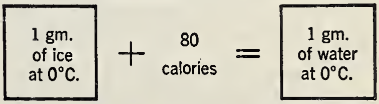


Fig. 328. Heat of fusion.

**★278. How can heat of fusion be measured?** To find the number of calories needed to melt one gram of a solid, which is its heat of fusion, we use the method of mixtures. We know that hot water will melt ice, for example, and we can find how many grams of ice can be melted by a known weight of water at a known temperature. We need the following data: weight of calorimeter; weight of water; weight of ice; initial temperature of hot water; and the final temperature when all the ice is melted.

Problem. A calorimeter weighing 100 gm. has a sp. ht. of 0.09; it contains 400 gm. of water at 40° C.; 91 gm. of *dry* ice are introduced. When the ice is all melted the temperature is 18.2° C. What is the heat of fusion of the ice?

*Solution.* Both calorimeter and water lose heat as follows:

$100 \times (40 - 18.2) \times 0.09 = 196.2$ calories (lost by calorimeter).

$400 \times (40 - 18.2) \times 1.00 = 8720$ calories (lost by water).

Total calories lost $= 8916.2$

These 8916.2 calories did two things: first, they melted 91 gm. of ice; second, they warmed the 91 gm. of water thus formed from 0° C. to 18.2° C.

$91 \times (18.2 - 0) \times 1.00 = 1656.2$ calories gained by water.

$8916.2 - 1656.2 = 7260$ calories, which were used to melt the ice.

$7260 \div 91 = 79.8$ calories used to melt 1 gram of ice, or its heat of fusion.

Suggestion. The student will do well to

remember that one gram of ice water is formed for every gram of ice that melts. As this ice water is being warmed to the final temperature, it takes part of the heat from the hot water.

**279. Heat is set free when water freezes.** We have learned that heat must be added to a solid to melt it. When a liquid solidifies or freezes, it seems natural to expect that heat will be liberated, because energy is indestructible. As a matter of fact, when one gram of water at 0° C. freezes, it sets free 80 calories of heat to the surrounding medium. The air in winter is warmed by the heat liberated during the formation of snow and ice. For this reason, the weather often moderates just before or during a snowstorm. Tubs of water in cellars may give off enough heat upon freezing to protect canned fruits and vegetables from freezing.

**280. Heat is absorbed in solution.** Dissolving salt in water lowers the temperature. A still more decided lowering of the temperature occurs when sal ammoniac, potassium iodide, or ammonium sulfocyanide is dissolved. Some of the heat energy of the solvent is used in dissolving the solute. Because heat energy breaks down the solid, heating the solvent not only causes a substance to dissolve more rapidly, but in almost all cases it increases the total quantity that can be dissolved.

**281. When are freezing mixtures necessary?** We cannot make ice cream or frozen puddings by the use of ice alone. The melting point of the ice is approximately the same as that of the substance to be frozen. When salt is put on ice it dissolves in the surface moisture. But a solution of salt in water freezes at a lower temperature than pure water. In fact the freezing point of a saturated solution of salt in water is − 22° C. Since the salt solution has a lower melting point than water, salt added to ice makes the ice melt rapidly. Both the melting of the ice and the dissolving of the salt absorb heat. Taking heat from the cream or the pudding lowers its temperature. If we continue to take heat away from a liquid, it will eventually be cooled below its freezing point.

## QUESTIONS

1. Why does snow "pack"? Why is it impossible to make snowballs if the temperature is much below 32° F.?

2. Why is the climate along the shores of Lakes Erie and Ontario suitable for fruit-growing?

3. Which cools a refrigerator more, 1 lb. of ice or 1 lb. of ice water? Explain.

4. Explain how regelation helps in the movement of valley glaciers.

5. Which will keep warm longer in a sick room, a 7-lb. flatiron, or 4 lb. of hot water, if both have the same original temperature?

6. Compare the climates of New York and Honolulu. How do you account for the difference?

7. Why do snow and ice melt so slowly in the spring?

8. How would "flood conditions" be affected if the heat of fusion of ice were 10 instead of 80?

9. A spoonful of "water ice" seems much colder to the tongue than a spoonful of ice cream. Explain why. Do you think a thermometer would show any difference?

10. Why does salt thrown on icy sidewalks help to melt the ice?

11. For use in making type, would you use a metal that expands when solidifying, or one that contracts?

12. What is the meaning of the expression, "A thick slice of bread furnishes 100 large Calories"?

## PROBLEMS

### Group A

1. How many calories are needed to warm 500 gm. of iron 40° C.? How many calories are needed to warm 500 gm. of lead 40° C.?

2. How many calories are needed to melt 200 gm. of ice? How many additional calories are required to warm the resulting ice water to 60° C.?

3. A calorimeter weighs 110 gm. Its sp. ht. is 0.1. If it has a temperature of 10° C., how many gm. of water at 50° C. must be poured into it to raise its temperature to 35° C.?

4. A piece of iron weighing 200 gm. has a temperature of 200° C. It is added to 400 gm. of water at 20° C. If the final temperature of the mixture is 29° C., what is the sp. ht. of iron?

5. How many B.T.U.'s will be needed to raise the temperature of 50 lb. of stone from 40° F. to 500° F., if the sp. ht. of stone is 0.4?

6. If 25 gm. of water at 80° C. are added to 25 gm. of ice at 0° C., how much water will be formed when the final temperature is reached, and what will be the final temperature?

7. 300 gm. of metal at 98° C. are mixed with 526 gm. of water at 20° C. If the temperature rises to 26° C., what is the sp. ht. of the metal?

8. A calorimeter, sp. ht. 0.1, wt. 100 gm., holds 100 gm. of water at 20°C. A platinum ball weighing 60 gm. is taken from a furnace and plunged into the water. The temperature of the water and calorimeter rises to 45° C. What was the temperature of the ball?

9. 200 gm. of metal having a temperature of 100° C. are plunged into 400 gm. of water at 20° C. The temperature rises to 28° C. What is the sp. ht. of the metal? How many gm. of ice at 0° C. can be melted by 200 gm. of the metal at 100° C.?

### Group B

10. A metal ball weighing 400 gm. has a temperature of 250° C. It is found that it gives out enough heat to melt 250 gm. of ice. What is its specific heat?

11. An aluminum container weighs 2 lb. Its temperature is 68° F. Two soapstone discs weighing 6 lb. each are heated to 400° F. and placed in the container. The discs have a sp. ht. of 0.2; the sp. ht. of aluminum is 0.2. A 5-lb. roast, having a sp. ht. of 0.5, is then placed in the container. If the original temperature of the roast was 68° F., find the temperature to which it will be heated by the soapstone discs.

12. A glass tumbler has a sp. ht. of 0.2. It weighs 300 gm. and has a temperature of 60° C. A certain amount of ice was added to the tumbler. The ice was all melted and the final temperature was 10° C. How many gm. of ice were added?

13. 150 gm. of ice at 0° C. are stirred in 500 gm. of water at 70° C. until the ice has all melted. What is the final temperature?

14. 300 gm. of ice, 500 gm. of ice water, and 1200 gm. of water at 100° C. are all mixed. What is the final temperature?

15. How many grams of ice can be melted by 200 gm. of zinc at 200° C.?

## 3. Vaporization and Condensation

**282. What is vaporization?** Just as the addition of heat to a solid changes it into a liquid, so a liquid may be changed into a gas or vapor by the addition of heat. The process of converting a liquid into a vapor is called *vaporization*. As the liquid is warmed, the more rapidly moving molecules escape from the surface. We call this process *evaporation*.

If we put a basin of water over a gas flame, bubbles of water vapor soon begin to form at the bottom of the basin. As these bubbles rise through the cooler layers of liquid above them, they collapse, causing the familiar "singing" so often noticed before liquids begin to boil. When the entire liquid is hot enough so that these bubbles reach the surface freely, vaporization occurs throughout the liquid with visible disturbance. Such vaporization is called *boiling* or *ebullition*.

**283. How fast do liquids evaporate?** So many factors affect the rate at which liquids evaporate that there is no short answer to this question. Since molecules disappear from the surface of the liquid during evaporation, anything that causes molecules to escape from the surface more rapidly will accelerate evaporation. Several facts, sometimes called the LAWS OF EVAPORATION, can be listed:

1. *Effect of temperature.* You know that hot water evaporates faster than cold water. This is what one would expect because heat increases the rate at which the molecules move. Therefore, we conclude that *the rate of evaporation increases with an increase in temperature.*

2. *Effect of area.* Suppose that we have a quart of water in a deep, narrow vessel and another quart in a broad, shallow pan. Common sense leads us to believe that more molecules can escape in a given time from a surface of 100 sq. in., for example, than from one of 5 sq. in., and the facts justify our belief. Hence we conclude that *the rate of evaporation increases as the surface area of the liquid increases.*

3. *Nature of liquid.* Alcohol evaporates much faster than water; ether evaporates much faster than alcohol; but some liquids like glycerine and olive oil hardly evaporate at all. We find that the *rate of evaporation varies with the nature of the liquid itself.*

4. *Effect of air above liquid surface.* If you wished to break the world's record in a 100-yd. dash, you would not go to a busy street intersection in a city to make the attempt. Too many collisions would impede your progress. There is no doubt but that some of the water molecules, attempting to escape from the surface by evaporation, collide with air molecules. Some of them doubtless rebound into the liquid again. (See Fig. 329.) If some of the air above the liquid surface is removed, the collisions will be less frequent, and the rate of evaporation will be accelerated. It becomes very rapid in a vacuum. Hence we conclude that the *rate of evaporation is increased when the atmospheric pressure is reduced.*

5. *Effect of humidity.* As water molecules escape from the surface, they occupy a part of the space between the air molecules, thus making a more crowded barrier for the molecules trying to escape. (See Fig. 330.) Now some water molecules will collide with *other water molecules* and rebound to the liquid. As the air becomes more nearly saturated with water vapor, the evaporation will be very slow. When the number of water molecules returning per second to the water surface exactly equals the number of water molecules escaping per second, the air is *saturated with water vapor. The rate*

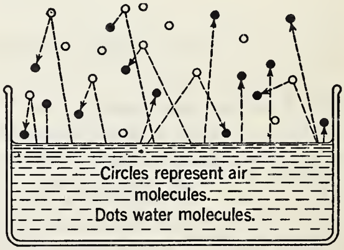


Fig. 329. Air molecules retard evaporation.

*of evaporation of water is decreased when the humidity of the air is increased.*

6. *Effect of wind.* Wet clothes dry rapidly on a windy day. The perspiration evaporates rapidly from our bodies when we sit in a draft. The saturated air in the immediate vicinity is removed by the wind and replaced by fresh, unsaturated air. We conclude that *the rate of evaporation increases with the rate of change of the air in contact with the liquid surface.*

**284. Do solids evaporate?** Possibly the laundress hangs out the clothes on a cold wintry day. The water freezes, but in a few hours the clothes will be found to be dry, even though the temperature was below freezing all the time. The ice must have evaporated. The molecules of solids are in constant motion, too, but they move more slowly than those of liquids. Such solids as snow and ice, camphor gum, iodine, musk, "moth balls" (naphthalene), etc., slowly disappear by evaporation. The vapor pressure of ice at 0° C. is equal to about 4.5 mm. of mercury. If a substance passes from a solid to a gaseous state, without appearing to liquefy, and then condenses again directly to a solid, it is said to *sublime.* Such solids as iodine can be purified by *sublimation.*

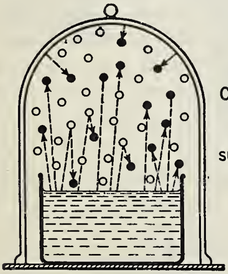


FIG. 330. Vapor is saturated.

**285. How does pressure affect the boiling point?** Let us refer to table 9, Appendix B, to see how raising the temperature affects the pressure which the water vapor exerts contrary to the air pressure above its surface as it escapes by evaporation. We may think of these two forces as opposing one another, the water molecules trying to escape, and the air pressure on the surface of the liquid trying to prevent their escape. Let us plot a curve, using the pressures at ten-degree intervals from 0° C. to 100° C. as ordinates and the temperatures as abscissas. (See Fig. 331.)

At a temperature of 100° C., the pressure of water vapor is 760 mm. of mercury, or one atmosphere. We say that the *boiling point of water at 760 mm. of mercury is 100° C.,* because at that temperature its saturated vapor exerts a pressure equal to that amount. If the air pressure is reduced to 525.4 mm. of mercury, water will boil at 90° C. If we increase the pressure to 787 mm. of mercury, water boils at

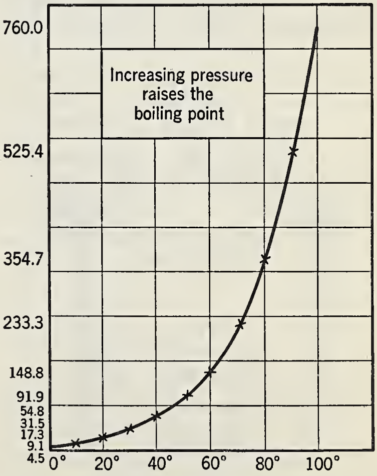


FIG. 331. Boiling point varies with pressure.

101° C. If we reduce the pressure to 733 mm., water boils at 99° C. Hence, we conclude that *the boiling point of water increases as the air pressure upon its surface increases.* Near the boiling point, a variation in pressure equal to 27 mm. of mercury will cause a variation of 1° C. in the boiling point.

**286. Why is pressure cooking necessary?** If you live in Denver, Colorado, or in Quito, Ecuador, you find that the air pressure is so low that water boils at from 90° C. to 95° C. At an elevation of about 900 ft. above sea level, the boiling point of water is about 1° C. lower than at sea level. At Denver, then, about one mile above sea level, boiling water is hardly hot enough to hard-boil eggs, and it takes a long time to cook potatoes and vegetables by boiling.

At high altitudes, pressure cookers are much used. Such cookers are strong-walled vessels. The foods are put into the cooker, a little water added, and then a thick lid is clamped on so tightly that steam cannot escape. When the water boils, the pressure of its saturated vapor is *added* to the pressure of the air inside the cooker. As the pressure rises, the boiling point rises, too. In such a cooker the temperature may rise to 110° C., or even to 120° C. Foods cook in about half the time at 110° C. that they do at 100° C. At a gauge pressure of 25 lb., potatoes cook in about 10 minutes and a pot roast is finished in about 40 minutes. To save time, pressure cookers are also used in many localities at low altitudes. They find use in canning vegetables and meats, since sterilization is more complete at higher temperatures. (See Fig. 332.)

**287. How are vacuum pans used?** Let us take a round-bottomed flask, add to it a little water, and heat the water to boiling. Then we may remove the flame and stopper the flask tightly. Let us next turn the flask upside down and clamp it in position as shown in Fig. 333. The flask is full of water and steam. If we dip a sponge in cold water, and let the water flow over the bottom of the flask, some of the steam

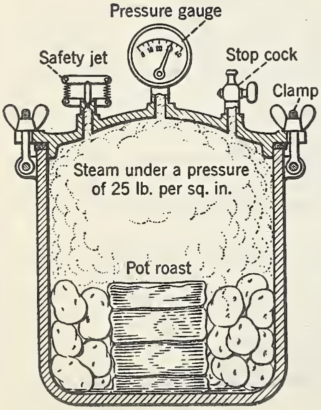


Fig. 332. Cooking under increased pressure.

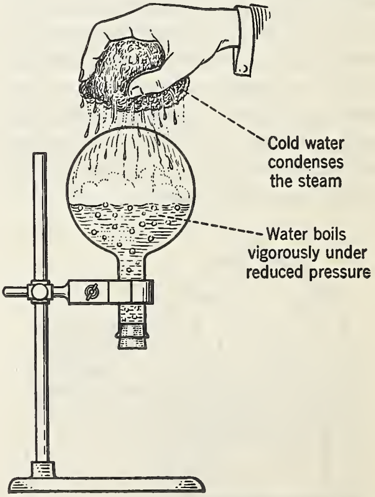

Cold water condenses the steam
Water boils vigorously under reduced pressure

Fig. 333. Lowering the pressure lowers the boiling point.

inside condenses and produces a *partial vacuum.* The water will start boiling vigorously under the reduced pressure. When the boiling stops, it can be started again by applying more cold water. The experiment can be continued until the water is really boiling at room temperature, or a little above.

The principle of boiling under reduced pressure is used in *vacuum pans.* Sugar crystals may be obtained from a sugar syrup by boiling the syrup in a vacuum pan. The liquid evaporates more rapidly, and the temperature is low enough so that there is no danger of scorching the sugar. Dyestuffs and other chemicals are dried in this manner.

**288. What are the laws of boiling?** Several facts concerning boiling liquids have been determined. We know that a liquid does not boil until the pressure of its saturated vapor equals the pressure upon the surface of the liquid. The temperature at which this condition occurs is called the *boiling point.*

1. The boiling point is sometimes used to identify liquids or to determine their purity. This is possible because *every pure liquid has a definite boiling point under the same conditions of pressure.*

2. A liquid does not get hotter as it continues to boil. Water boiling vigorously has the same temperature as water boiling slowly. Hence we conclude that *the boiling point of a pure liquid does not change, but it remains constant until all the liquid has vaporized.*

3. From what we learned in the preceding sections, we know that *the boiling point of a liquid rises as the atmospheric pressure increases, and falls as the pressure decreases.*

4. Solids or gases dissolved in liquids change the boiling point of the liquids. Salt water boils at a higher temperature than fresh water. In general, *solids dissolved in liquids raise the boiling point. Gases dissolved in liquids usually lower the boiling point.*

5. When two or more liquids having different boiling points are mixed, the mixture has a different boiling point. Generally, its boiling point is some temperature between the boiling points of the pure liquids. For example, water boils at 100° C., and alcohol at 78° C. A mixture of the two will usually boil at some temperature between 78° C. and 100° C.

**289. What is distillation?** For some purposes it is desirable to have water which is free from mineral matter. Any impurities *dissolved* in water cannot be removed by filtering. If we vaporize the water, the mineral matter that had been dissolved remains behind, and the pure water vapor can then be condensed. An apparatus convenient for this process, which is called *distillation,* is shown in Fig. 334. The distilling flask contains the impure water. As it boils, the vapor passes through the inner tube of the condenser, and it is cooled by the cold water which flows through the outer tube. Distilled water is used in storage batteries for automobiles, and in making up many solutions in chemical laboratories.

The pupil must not get the idea that distillation merely means purifying water. Many liquids are distilled to purify them. It is really *a complex process which consists in first vaporizing a liquid and then condensing its vapor.* Dew is distilled water.

**290. What is meant by fractional distillation?** Possibly your father puts alcohol in the radiator of his car in winter as an antifreeze. The boiling point of such alcohol is about 80° C.

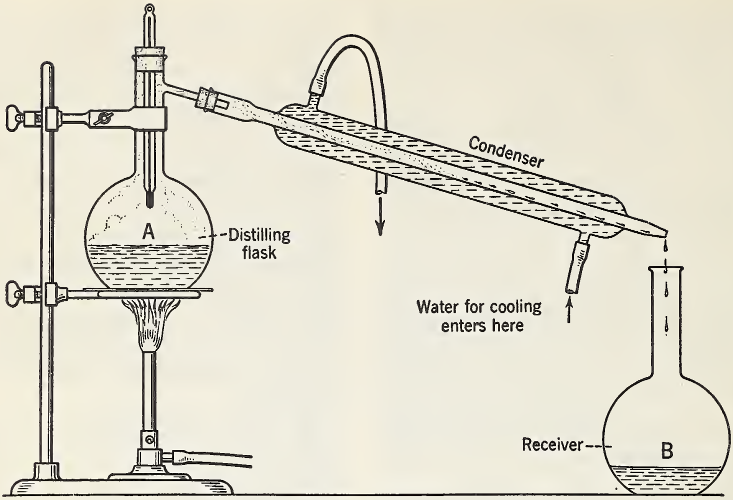


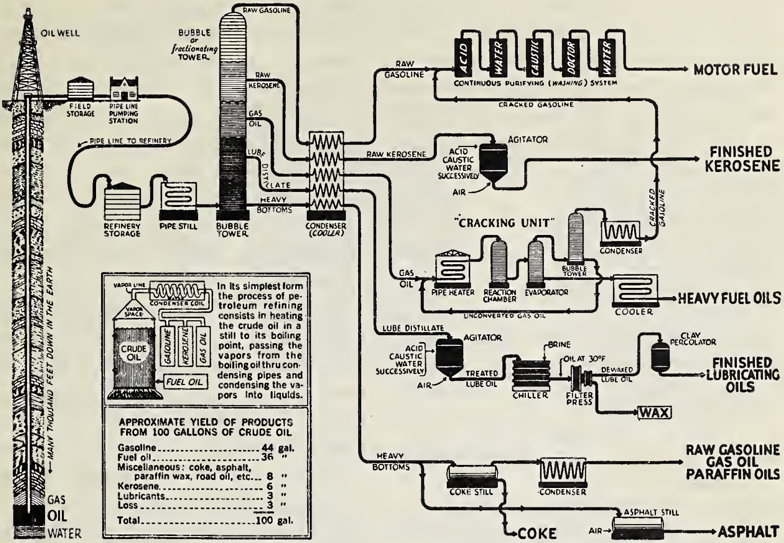
FIG. 334. Purification by distillation.

and that of the water with which it is mixed is about 100° C. When the engine gets warm, the alcohol vaporizes faster than the water does. In other words, one fraction of the liquid distils off faster than the other fraction. It is possible to separate two or more liquids which have different boiling points by distilling off one portion and collecting it, then raising the temperature and distilling off a second portion.

Petroleum, or crude oil, is a mixture of a number of liquids which have different boiling points. Some of the most important products obtained from petroleum are gasoline, kerosene, lubricating oils, fuel oils, petroleum jelly, and paraffin. When petroleum is heated in a huge distilling flask, the products which have low boiling points boil off first, followed in order by those of increasingly higher boiling points. The process of separating such a mixture is called *fractional distillation.* Fig. 335 shows a *still* and *fractionating column* used in the refining of petroleum.

Some complex solids, such as wood and coal, yield many different products when they are *dry* distilled. The solid is put in a large retort and strongly heated. Some of the products which escape are gaseous, some of them are liquid, and some of the residues left in the retort are solid. This process is called *destructive distillation.*

**291. How much heat is needed to vaporize one gram of water?** Let us put a quart of ice water on a gas burner and find how long a time it takes to heat it to the boiling point. Of course, every gram of the water has absorbed 100 calories of heat in being warmed from 0° C. to 100° C. But if we continue to watch the time, we shall find that the water "boils away" slowly. In fact, it will take *more than five times as long* to change the boiling water into steam or vapor as it did to warm it up to its boiling point. All the time that the boiling water was being changed to steam, it was absorbing heat. Here again, the heat absorbed is


OIL WELL
FIELD STORAGE
PIPE LINE PUMPING STATION
PIPE LINE TO REFINERY
REFINERY STORAGE
PIPE STILL
BUBBLE or fractionating TOWER
BUBBLE TOWER
RAW GASOLINE
RAW KEROSENE
GAS OIL
LUBE DISTILLATE
HEAVY BOTTOMS
CONDENSER (COOLER)
RAW GASOLINE
ACID
WATER
CAUSTIC
DOCTOR
WATER
CONTINUOUS PURIFYING (WASHING) SYSTEM
MOTOR FUEL
CRACKED GASOLINE
RAW KEROSENE
AGITATOR
ACID CAUSTIC WATER SUCCESSIVELY
AIR
FINISHED KEROSENE
"CRACKING UNIT"
GAS OIL
PIPE HEATER
REACTION CHAMBER
EVAPORATOR
BUBBLE TOWER
CONDENSER
CRACKED GASOLINE
COOLER
HEAVY FUEL OILS
UNCONVERTED GAS OIL
LUBE DISTILLATE
AGITATOR
ACID CAUSTIC WATER SUCCESSIVELY
AIR
TREATED LUBE OIL
BRINE
CHILLER
OIL AT 30°F
FILTER PRESS
DEWAXED LUBE OIL
CLAY PERCOLATOR
FINISHED LUBRICATING OILS
WAX
HEAVY BOTTOMS
COKE STILL
CONDENSER
RAW GASOLINE GAS OIL PARAFFIN OILS
ASPHALT STILL
AIR
ASPHALT
COKE
← MANY THOUSAND FEET DOWN IN THE EARTH
GAS
OIL
WATER
VAPOR LINE
CONDENSER COIL
VAPOR SPACE
CRUDE OIL
GASOLINE
KEROSENE
GAS OIL
FUEL OIL

In its simplest form the process of petroleum refining consists in heating the crude oil in a still to its boiling point, passing the vapors from the boiling oil thru condensing pipes and condensing the vapors into liquids.

APPROXIMATE YIELD OF PRODUCTS FROM 100 GALLONS OF CRUDE OIL

| | | |
|---|---|---|
| Gasoline | 44 | gal. |
| Fuel oil | 36 | " |
| Miscellaneous: coke, asphalt, paraffin wax, road oil, etc. | 8 | " |
| Kerosene | 6 | " |
| Lubricants | 3 | " |
| Loss | 3 | " |
| Total | 100 | gal. |

*Courtesy of the Socony-Vacuum Company*

Fig. 335. Crude petroleum is separated into many different products by fractional distillation.

latent (hidden), since it cannot be shown by a thermometer. We are thus led to believe that it takes more than 500 calories of heat to change one gram of boiling water into steam which has the same temperature. *The heat required to vaporize one gram of a substance without changing its temperature is called its heat of vaporization.*

It is extremely difficult to measure the heat of vaporization of water accurately. The values generally accepted range from 535 to 540, with many authorities agreeing upon 539 as the most accurate number. For solving problems, we shall use the number 540, since it simplifies numerical multiplications, and it is reasonably accurate. Hence, we conclude that *one must add to 1 gm. of boiling water at 100° C. 540 calories of heat to change it into steam at 100°* C. (See Fig. 336.) Then it will take 972 B.T.U.'s to change 1 lb. of boiling water at 212° F. into steam at the same temperature. To vaporize 1 gm. of alcohol, 205 calories are needed. The heat of vaporization of liquid ammonia is 295 calories. We shall see later that the high heat of vaporization of ammonia makes it useful in making artificial ice.

**★292. How can heat of vaporization be found?** Here, too, we use the method of mixtures. Steam is passed into cold water, as shown in Fig. 337, and the increase in temperature noted. The trap collects all the water formed from the steam which condenses before it passes into the calorimeter. One needs

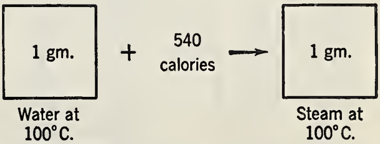

1 gm.
+
540 calories
1 gm.
Water at 100°C.
Steam at 100°C.

Fig. 336. Heat needed to vaporize one gram of water.

to know the weights of calorimeter, water, and steam. It is necessary, too, to know the original temperature of the steam, the water, and the calorimeter, as well as the final temperature of the mixture. Suppose that we get the following data:

| | |
|---|---|
| Weight of calorimeter......... | 120 gm. |
| Specific heat of calorimeter.... | 0.1 |
| Weight of water.............. | 402 gm. |
| Weight of steam............. | 23.5 gm. |
| Initial temperature of the cold water..................... | 6° C. |
| Final temperature of water.... | 40° C. |
| Temperature of steam........ | 100° C. |

Computations:

120 × (40 − 6) × 0.1 = 408 calories, absorbed by calorimeter.

402 × (40 − 6) × 1.0 = 13,668 calories, absorbed by water.

Total calories absorbed = 14,076.

When 23.5 gm. of steam condense, 23.5 gm. of water at 100° C. are formed.

23.5 × (100 − 40) × 1.00 = 1410 calories, lost by water in cooling through 60° C.

14,076 − 1410 = 12,666 calories, lost by steam in condensing.

12,666 ÷ 23.5 = 538.9 calories, lost by 1 gm. of steam in condensing.

**293. Water gives out heat as it condenses.** We know that energy cannot be destroyed, and for that reason the heat that is absorbed during vaporization must be *set free* again during condensation. In the boiler of our furnace, the heat from the burning fuel changes the water into steam. The steam expands and rises to the radiators. There every gram of steam that condenses sets free the 540 calories which it had absorbed during vaporization. Thus heat is given out to the room by the radiators.

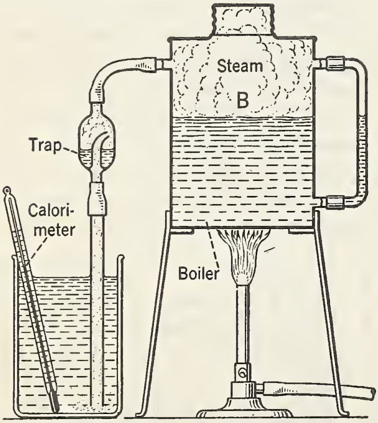


FIG. 337. How to find heat of vaporization.

Every housewife knows that steam produces a much more severe burn than boiling water. Both may have the same temperature. But every gram of steam that condenses on a hand or arm sets free the 540 calories it had absorbed while it was being changed to vapor. After it has given up its 540 calories, each gram of steam can still liberate as much heat as a gram of boiling water.

**294. Why does evaporation produce a cooling effect?** If we wet one hand and then step out-of-doors on a cold day in winter, the hand that was wet will be decidedly colder than the other. Every gram of water that evaporates takes 540 calories of heat from the skin. Such subtraction of heat must cause a cooling effect. The skin is a delicate *thermostat*. We perspire when we get too warm. If the perspiration evaporates, the skin is cooled. If we sit in a breeze where the perspiration evaporates more rapidly, we are cooled more decidedly. If the air is very humid on a hot day, we suffer from the heat because the perspiration does not evaporate and cool us. Alcohol is used for a sponge bath to reduce fever. It evaporates faster than water and cools the skin more. Ether boils at about 35° C. It evaporates so fast when poured on the hand that it makes the hand feel very cold.

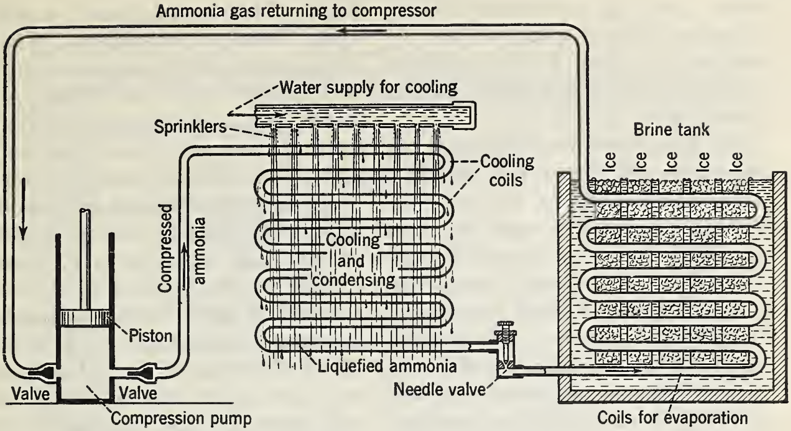

Ammonia gas returning to compressor
Water supply for cooling
Sprinklers
Cooling coils
Brine tank
Ice
Ice
Ice
Ice
Ice
Compressed ammonia
Cooling and condensing
Piston
Liquefied ammonia
Needle valve
Valve
Valve
Compression pump
Coils for evaporation

FIG. 338. Diagram of a plant for making ice.

Our streets are sprinkled in hot weather. The heat needed to vaporize the water comes from the hot pavement and the surrounding air, and both are cooled.

Let us put a few drops of water on a wooden block, place a watch glass convex side down in the water, and pour a couple of teaspoonfuls of ether onto the watch glass. If we put the whole apparatus under a bell glass and exhaust the air from the bell glass rapidly, the ether will boil away quickly under the reduced pressure. The rapid evaporation of the ether will take heat from the thin film of water under the watch glass so rapidly that the water will freeze. At the end of the experiment we shall find the watch glass frozen to the wooden block.

**295. What principle is used in making ice?** On a small scale, ice was formed in the experiment just described. To make ice commercially, one depends upon the *cooling effect of evaporation.* The faster the evaporation, the greater the cooling effect. Ether produces a greater cooling effect than alcohol, and alcohol a greater cooling effect than water. Suppose we use a liquid which boils at − 34° C. Then the cooling effect becomes intense.

At room temperature, ammonia is a light gas, but it can be converted into a liquid by compressing it and cooling it at the same time. When it evaporates, every gram of it absorbs about 295 calories of heat from the medium which is in contact with it.

Let us study Fig. 338. Ammonia gas is compressed in the cylinder by the piston. The heat of compression is absorbed by the cold water which flows down over the cooling coils, and the ammonia liquefies. As the liquid ammonia flows through the expansion valve into the coils of the brine tank, it evaporates and expands. Both produce a cooling effect, and the brine which surrounds the coils is cooled, possibly to − 10° C. or lower. The cans of fresh water which are immersed in the brine are frozen into cakes of solid ice in from 24 to 48 hours.

In cold storage plants, the cold brine is pumped through pipes in storage rooms. Just as hot water flowing through a radiator warms a room by radiation, so cold brine circulating through coils of pipe will cool a room to any desired temperature.

**296. How does the mechanical refrigerator work?** *Electric type.* In many homes and apartment houses, electricity is now used to make ice or to keep refrigerators cool. A small electric motor of about one-sixth horsepower is used to operate a small compressor. The gas used may be sulfur dioxide, because it is so easily liquefied. In many of the new refrigerators methyl chloride or di-chloro-di-fluoro methane is now used. (See Fig. 339.) Air circulates freely around the coils to absorb the heat produced by compressing the gas. Then the liquid refrigerant is led to the coils in one compartment of the refrigerator. As it evaporates in these coils, it absorbs heat from the surrounding air, thus cooling the refrigerator compartments and the food in them. Pans of water placed inside the coils are converted into ice as the heat from the water, too, is absorbed during the evaporation of the refrigerant.

*Gas type.* Michael Faraday, of whom we shall learn more later, devised an ingenious method of liquefying gases. A thick-walled tube of the type shown in Fig. 340 was filled with chlorine gas. One end of the tube was packed in a freezing mixture of salt and ice, while the other end was being heated. Heating one end of the tube *compressed* the gas in the other end, where it was liquefied as the freezing mixture cooled it. By a similar method of compressing gases by heating them in a confined space and cooling them, Faraday liquefied several different gases.

The gas refrigerator, which uses the slogan "Flames that freeze," is based upon Faraday's experiments. Water, ammonia gas, and hydrogen are placed in a series of pipes and sealed. Ammonia gas is extremely soluble in water, but it is driven out of the water by the heat of a gas flame. The rapid expulsion of the ammonia gas from the water *compresses* it until it liquefies upon being simultaneously cooled. Methyl chloride is used to circulate around the pipes where compression is taking place and to cool the ammonia by absorbing its heat of compression. The liquid ammonia evaporates and expands inside the coils in the refrigerator compartment, thus producing the cooling effect. The ammonia then redissolves in the water. The hydrogen prevents the formation of a vacuum by the rapid solution of the ammonia gas, and thus prevents "pounding." The process is repeated continually. The gas refrigerator is silent in its operation, since there are no moving parts.

**297. How are gases liquefied?** Faraday made a list of several *fixed* gases, as he called them, because he could not liquefy them by the method described in the preceding section. Such gases as hydrogen, oxygen, and air, for example, cannot be liquefied by pressure alone. It is necessary to cool air to − 140° C. before it can be liquefied by any pressure, however great. The temperature to which any gas must be cooled before it can be liquefied by pressure is called its *critical temperature.*

The pressure needed to liquefy a gas at its critical temperature is called its *critical pressure.* All gases have now been liquefied, by subjecting them to high pressure, and then cooling them by expansion. Successive compressions

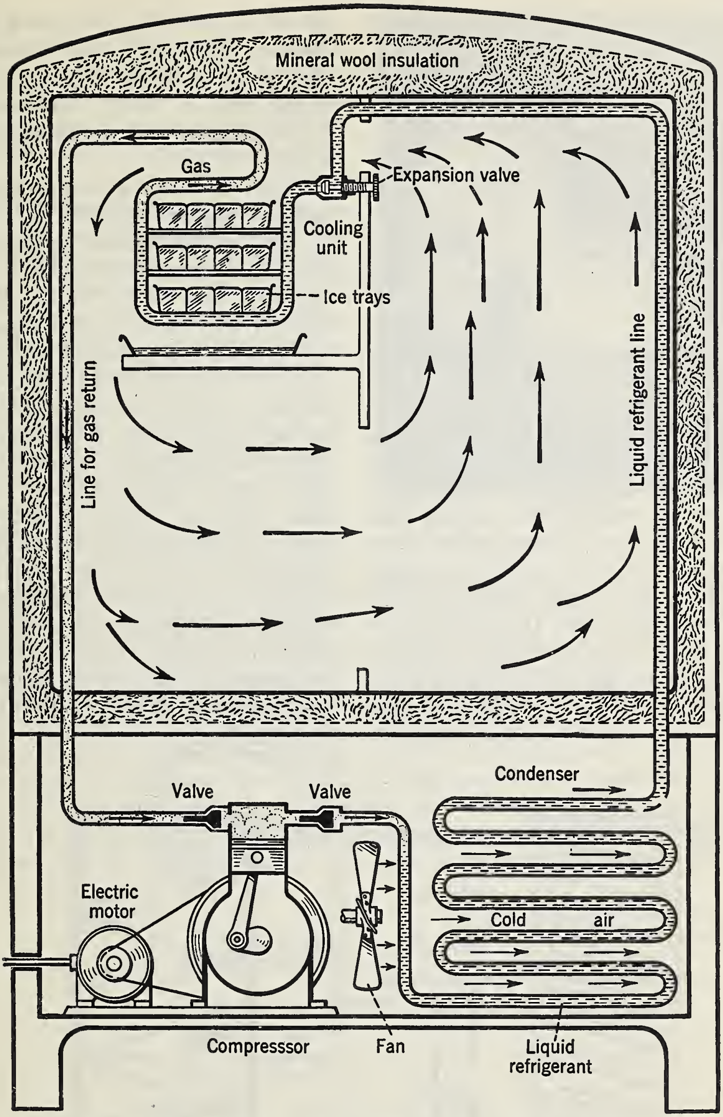

Mineral wool insulation
Gas
Expansion valve
Cooling unit
Ice trays
Line for gas return
Liquid refrigerant line
Condenser
Valve
Valve
Electric motor
Cold
air
Compresssor
Fan
Liquid refrigerant

FIG. 339. A mechanical refrigerator of the household type. The compressor is driven by a small electric motor. Cold air is blown over the cooling coils by means of a revolving fan. The heat needed to evaporate the refrigerant is taken from the water in the trays. Subtracting heat from water will eventually cause it to freeze.

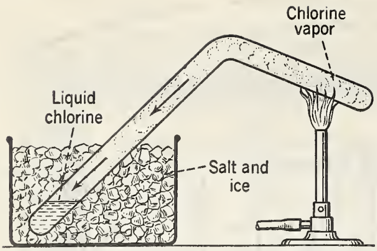


FIG. 340. In such a tube Faraday succeeded in liquefying several different gases.

and coolings are necessary in the case of those gases that have very low boiling points.

**298. How is liquid air made?** In an apparatus of the type shown in Fig. 341, air is first compressed. Then it circulates through the cooling coils where the heat of compression is absorbed. It expands rapidly as it escapes through the needle valve and it is thus further cooled. It cools the air in the inner of the concentric coils as it returns through the outer coils to the compressor. By continually compressing the air, absorbing the heat of compression, and then letting it expand, some of the air at the end of the concentric coils is finally cooled to its critical temperature, and changes into a liquid.

Liquid air under atmospheric pressure boils at from − 182° C. to − 194° C., the variation depending upon the per cent of nitrogen present. Liquid hydrogen boils at − 253° C. If we throw a piece of ice into a vessel of liquid air, it will probably boil over. The ice is so hot compared to the liquid air that it makes it boil vigorously. Boiling water is only 100 Centigrade degrees hotter than ice, but ice is more than 180 Centigrade degrees hotter than liquid air. Rubber tubing immersed in liquid air soon becomes hard and brittle. It can be easily broken by hitting it with a hammer. Mercury and alcohol may be frozen solid by pouring liquid air over them. In an open vessel standing on a cake of ice, liquid air will boil vigorously. It may be kept for a

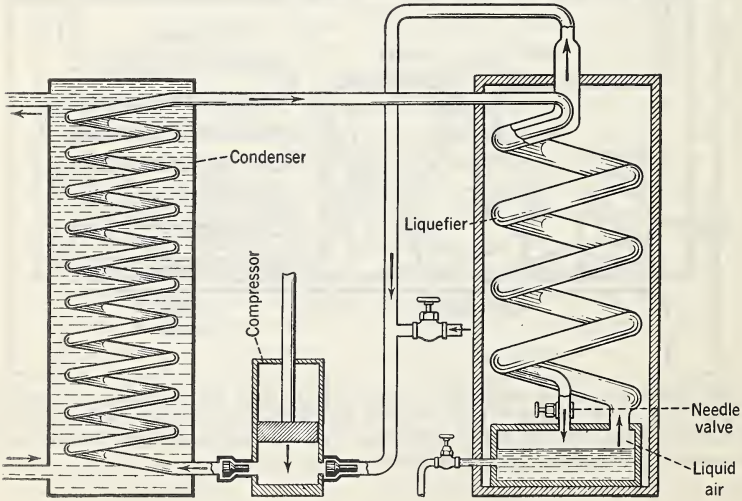
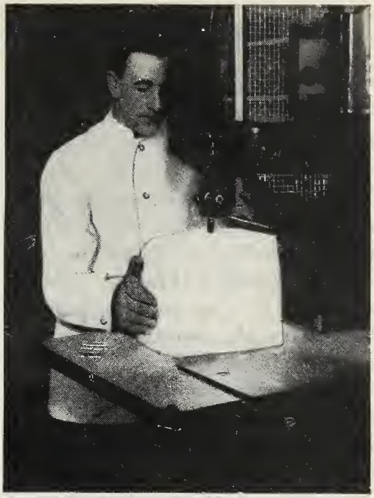


FIG. 341. One type of apparatus that may be used for liquefying air.

few hours in an unstoppered Dewar flask, which is a double-walled vacuum flask similar in construction to a thermos bottle.

Some gases that are easily liquefied are now marketed by forcing them into strong steel cylinders under high pressure. Carbon dioxide in liquid form is now marketed, and it is also sold in the solid state for use as a refrigerant. Because it sublimes, one manufacturer uses the name "Dry ice" for his product. It needs only a small quantity to produce the same cooling effect as a large piece of ice, since its temperature is about − 80° C. (See Fig. 342.)



*Courtesy of Pure Carbonic, Inc.*

FIG. 342. A workman cutting dry ice.

★**299. The effect of heat on water can be shown graphically.** Suppose that we plot a curve to show what changes take place when ice at − 10° C. is heated until it is all converted into steam under pressure at 120° C., using temperature changes as ordinates and heat units as abscissas. (See Fig. 343.) Since the specific heat of ice is 0.5, 1 gm. of ice absorbs 5 calories in being warmed to zero degrees; 80 calories are absorbed in melting the ice. *Note that there is no temperature change;* 100 additional calories are needed to warm the water to the boiling point. Another change of state occurs, in which 540 calories of heat are absorbed. If the steam, which has a specific heat of almost 0.5, is under pressure, 10 calories will be used to heat 1 gm. from 100° C. to 120° C. The student will find this curve helpful in solving problems involving specific heat, heat of fusion, and heat of vaporization. We see that it needs 720 calories of heat to change 1 gm. of ice at 0° C. into 1 gm. of steam at 100° C.

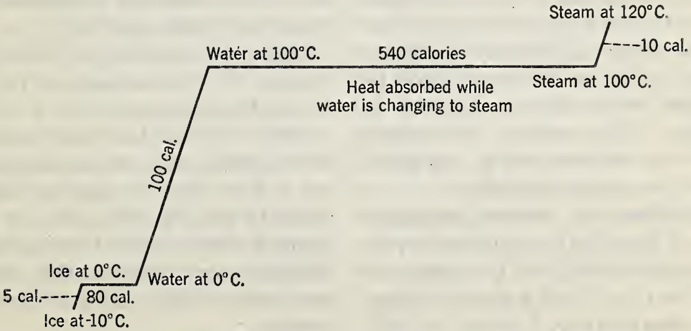


FIG. 343. Heat absorbed during a change of state and temperature.

## 4. Humidity

**300. What is meant by humidity?** Water is constantly evaporating, even when the temperature is 32° F. or lower. Hence, water vapor is always present in the air in greater or lesser amounts. The air over the ocean or along the seashore is likely to be more moist or "humid" than the air over the interior of a continent. Of course, winds carry the moisture to inland places when they blow shoreward. An increase in temperature also increases the amount of moisture in the air, provided there is a source of supply from which evaporation can take place.

**301. What is the capacity of the air?** The amount of moisture which the air *can* hold when it is *saturated* is called its *capacity*. Usually capacity is expressed in *grains per cu. ft.* Table 5, Appendix B, shows how many grains of moisture 1 cu. ft. of air *can* hold at various temperatures. Just as one would suspect, *the capacity increases with an increase in temperature.*

**302. What is absolute humidity?** We may have a bottle which holds one quart. That is its capacity or what it *can* hold. If we pour into the bottle one pint of milk, the amount of liquid which the bottle *does* hold is one pint. Just as a bottle of milk may not always be full, so the air may not always be saturated with moisture, or filled to capacity. The amount of moisture 1 cu. ft. of air *does* hold at any given time is its *absolute humidity.*

**303. What is relative humidity?** When a quart bottle contains one pint of liquid, it is 50% full. If a cubic foot of air that *could* hold 4 grains of water vapor *does* hold only 2 grains, it is 50% full, or half saturated. *The ratio of the amount of moisture which the air does contain to what it could contain is called its relative humidity.* We find relative humidity by dividing the absolute humidity by the capacity. It is usually expressed in per cent.

**304. How does temperature affect relative humidity?** A cold room usually feels damp. The same room feels "dry" a short time after a fire has been started in the room. The total amount of moisture in the room has not been reduced, but the capacity has been increased by the rise in temperature. Therefore, the *relative* humidity has been lowered. To illustrate, suppose that at 32° F. the air actually does hold 2 grains of water vapor per cu. ft. From the table, we see that the capacity at that temperature is 2.113 grains per cu. ft. The relative humidity equals 2 ÷ 2.113, or 94%. The air under such conditions feels damp. If the temperature is raised to 68° F., the amount of moisture will remain the same, but the capacity is increased to 7.48 grains per cu. ft. The relative humidity now equals 2 ÷ 7.48, or 26%. The air will now feel very dry. Hence *increasing the temperature decreases the relative humidity.*

Again, suppose that air at 84° F. contains 6.14 grains per cu. ft. The relative humidity equals 6.14 ÷ 12.356, or 49%. The air has three times as much moisture as in the preceding case, but it feels drier because its *relative* humidity is fairly low. If the air were suddenly cooled to 62° F., the relative humidity would rise to 100%. Therefore, *cooling the air increases the relative humidity.*

When the relative humidity is about

50%, the perspiration evaporates quite rapidly and we feel more comfortable than at either a very low or a very high relative humidity. If the relative humidity is too low, the skin becomes dry and chafed. Too high a relative humidity is just as uncomfortable, especially when the temperature is high. The body cannot be cooled in hot weather unless the perspiration evaporates readily.

**305. How do the wet-and-dry-bulb thermometers work?** The relative humidity may be found by using two thermometers, one having a dry bulb, the other a wet bulb. When the air is dry, the moisture evaporates rapidly from the wet bulb, lowering its temperature. The faster the evaporation, the greater the difference of temperature between the two thermometers. Tables have been constructed for showing the relative humidity directly from the difference between the two thermometer readings. The *hygrodeik*, Fig. 344, is an application of the same principle. The curves are so plotted that relative humidity, dew point, and absolute humidity may all be read directly. (See Table 16, Appendix B.)

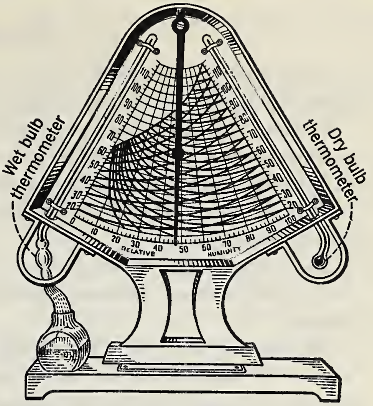


Fig. 344. The hygrodeik measures relative and absolute humidity and shows dew point.

**306. What causes precipitation?** Since cooling the air increases the relative humidity, it is possible to cool it until the relative humidity reaches 100%. *The temperature at which the moisture in the air begins to condense is called the dew point.* Before *precipitation* of any kind can occur, *the air must be cooled below the dew point.* Of course, the relative humidity can never exceed 100%, and the cooling of saturated air always results in some form of precipitation. If the air at 84° F. contains 8 gr. of water vapor per cu. ft., it will begin to lose moisture by condensation when cooled to 70° F., because the capacity of air at 70° F. is only 7.98 grains per cu. ft. If cooled to 60° F., every cu. ft. of air will lose about 2.25 grains of moisture. If the dew point is below 32° F., the precipitation will appear as frost or snow.

If one puts a thermometer into a test tube one half full of water and immerses it in a freezing mixture, he finds that it is possible to *supercool* the water several degrees below its freezing point without any ice being formed. If this *supercooled water* is disturbed by stirring it with the thermometer, it will freeze instantly, and the temperature will rise to 0° C. Clouds often contain masses of such supercooled drops of water or water vapor when they are calm and quiet. If an airplane enters such a cloud, the water drops instantly solidify and form a layer of ice on the wings and fuselage of the plane.

## Summary

The calorie is the amount of heat required to raise the temperature of 1 gm. of water 1° C. In heat exchange, calories lost equal calories gained.

Fusion is the process of changing from the solid to the liquid state. The temperature at which the change occurs is the melting point. Increase in pressure raises the melting point of substances that contract when solidifying, and lowers the melting point of substances that expand during solidification.

To change 1 gm. of ice at 0° C. to water at the same temperature requires 80 calories; the same amount of heat is lost when 1 gm. of water freezes.

The boiling point of a liquid may be defined as the temperature at which the pressure of its vapor equals the atmospheric pressure. An increase in pressure raises the boiling point; a decrease in pressure lowers the boiling point.

To change 1 gm. of water at 100° C. into 1 gm. of steam at the same temperature requires 540 calories; the same amount of heat is set free when the steam condenses.

Evaporation requires heat. This heat is taken from the surrounding medium, thus lowering its temperature. Artificial ice is made by the application of this principle.

The amount of water vapor air *can* hold at a given temperature is its capacity; the amount of water vapor the air *does* hold is its absolute humidity; absolute humidity divided by capacity equals relative humidity.

*How many of the following terms and phrases can you define or explain? (To be used as a review exercise.)*

Calorie
British thermal unit
Specific heat
Law of heat exchange
Speed of evaporation
Pressure, its effect on boiling point
Vacuum pans
Liquefaction of gases
Liquid air
Capacity of air
Relative humidity
Absolute humidity
Fusion
Solidification
Liquefaction
Heat of fusion
Vaporization
Pressure cooking
Laws of boiling
Fractional distillation
Cooling effect of evaporation
Mechanical refrigeration

## QUESTIONS

1. Why do streets dry so rapidly on a windy day?

2. Does fanning cool the face when one is not perspiring? Explain.

3. Food is sometimes kept in thick-walled porous vessels which have been immersed in water before using. Under what atmospheric conditions do you think such "iceless refrigerators" are fairly efficient?

4. Why is it difficult to keep cool in summer when the relative humidity is above 90%?

5. Is water any hotter when boiling vigorously in an open vessel than when boiling slowly? Try to find in the answer to this question a suggestion as to one method

you can use for reducing your gas bills.

6. Why do clothes sometimes "freeze dry"?

7. Why does steam produce a more severe burn than boiling water at the same temperature?

8. The steam that enters a radiator may be the same temperature as the water that leaves it. How has the room been warmed?

9. Why do snow and ice melt so slowly in the spring, even when the temperature is considerably above the freezing point?

10. Why is it difficult to hard-boil eggs in an open vessel at the top of Pike's Peak?

11. Explain why sea water freezes less easily than fresh water.

12. What are the advantages of the pressure cooker?

13. Look up the meaning of the word "autoclave." How is it like the pressure cooker? For what purpose is it used in biology and medicine?

14. The olla is an unglazed earthenware pot which finds use as a water bottle in hot countries. Explain how it can keep the water cool.

15. Very often the air is warm and sultry after a shower. Can you give an explanation of this fact?

16. Persons sometimes say that the air is likely to be warmer after a heavy snowstorm. Is it true? If so, explain.

## PROBLEMS

### Group A

1. How many calories of heat do 25 gm. of steam lose upon condensing?

2. How many grams of water are formed when 25 gm. of steam condense? After 25 gm. of steam condense, how many additional calories will be lost when the resulting water cools to 50° C.?

3. How many calories are set free when 40 gm. of steam condense and then cool to 0° C.?

4. How many gm. of ice can be melted by 60 gm. of steam?

5. How many calories are lost by 80 gm. of steam in condensing, cooling to 0° C., and then changing to ice at 0° C.?

6. How many gm. of ice at 0° C. are needed to lower the temperature of 1000 gm. of water from 90° C. to 20° C.?

7. How many calories of heat are needed to warm 200 gm. of water from 20° C. to 100° C.? How many additional calories are needed to convert the water into steam?

8. A calorimeter weighing 200 gm. has a sp. ht. of 0.1. If its temperature is 20° C., how many grams of steam are needed to supply the heat needed to raise the temperature of the calorimeter to 90° C.?

### Group B

9. What weight of aluminum at a temperature of 300° C. will be needed to melt, raise to the boiling point, and vaporize 150 gm. of ice at 0° C.? (In mixtures all substances reach the same final temperature.)

10. What will be the final temperature when 35 gm. of ice at 0° C. are mixed with 500 gm. of water at 60° C.? (*Hint.* Let $x$ equal final temperature. $500(60 - x)$ times $1.00 =$ calories lost. $35 \times 80$, plus $35(x - 0) \times 1 =$ calories gained.)

11. 200 gm. of ice, 400 gm. of ice water, and 50 gm. of steam are mixed. What is the resulting temperature?

12. 60 gm. of steam, 300 gm. of water at 100° C., 300 gm. of ice, and 500 gm. of ice water are mixed. What is the final temperature?

13. 10 gm. of steam at 150° C. are mixed with 200 gm. of ice water and 60 gm. of ice at − 20° C. Find the resulting final temperature.

14. How many B.T.U.'s are needed to melt, raise to the boiling point, and vaporize the resulting water when 50 lb. of ice are heated?

15. 10 gm. of steam at 100° C., 10 gm. of water at 0° C., and 10 gm. of ice at 0° C. are mixed. What will be the final temperature? How many grams of water are formed?

16. A ton of coal in burning supplies 12,000 B.T.U.'s per lb. How many tons of water at 50° F. can be converted into steam at 362° F., if we assume that 50% of the heat is lost by radiation? Consider the sp. ht. of steam as 0.5.

# *Heat — How It Is Distributed*

**307. How is heat distributed?** In an earlier chapter we learned that heat comes from the sun, from chemical action, and from wasted work. From the law of mixtures, we learned that heat can be transferred from one body to another. We want to know how heat gets from our furnaces in the basement to the rest of the house. If we learn how heat is distributed, we may be able to control such transfer of heat. In some cases we shall want to hasten the distribution of heat, and in other cases we shall attempt to prevent the escape of heat. Physicists list three important ways in which heat is transferred from one place to another: *conduction*, *convection*, and *radiation.*

## 1. Conduction

**308. What is conduction?** If one were so lacking in manners as to let the bowl of his sterling silver teaspoon stand in a cup of hot coffee, he would find the handle of the spoon hot enough to burn his fingers. When one end of a stove poker is held in some live coals, the other end of the poker will soon be too hot to be held comfortably. In some way, the heat is *conducted*, or *led*, from one end of each solid to the other end. The molecules of the live coals are in rapid vibration as they produce heat energy. The molecules of the poker which are adjacent to the coals receive some of this heat energy, which they transmit along the poker to other molecules. *Such transmission of heat from molecule to molecule is called conduction.*

**309. Do solids conduct heat?** From the preceding section we know that silver and iron are conductors of heat. By the use of a *conductometer*, Fig. 345, the ability of solids to conduct heat may be compared. The rods are covered with paraffin or with a paint which changes color when heated. When steam is passed through the base of the apparatus, the *relative* conductivity of the metal rods can be determined by the rate at which the

---

### Vocabulary

| | |
|---|---|
| Conduction | transmission of heat from molecule to molecule. |
| Convection | transmission of heat by the intermingling of the heated masses. |
| Radiation | transmission of heat energy by rays or waves. |
| Insulator | a substance that does not conduct heat. |
| Asbestos | a fibrous mineral that is neither flammable nor easily melted. |
| Brine | a solution of some salt, possibly common table salt. |
| Doldrums | the name given to the equatorial calm belt. |
| Annular | ring-shaped. |
| Horse Latitudes | tropical calm belts. |

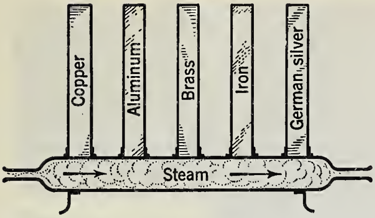


FIG. 345. Some metals conduct heat better than others.

paraffin melts or the paint changes color. The order of conductivity of the five metals shown here is as follows: copper, aluminum, brass, iron, and German silver.

Silver is the best conductor of heat known. Copper and aluminum are much better conductors than other common metals. German silver, which is an alloy of copper, zinc, and nickel, is not a particularly good conductor. Metals generally are much better conductors of heat than wood or stone. (See Table 13, Appendix B.)

The fibers used for clothing are rather poor conductors, although linen and cotton are better than wool and silk. Sawdust is a poorer conductor of heat than wood, because there are so many air spaces between the particles. For the same reason, furs and feathers are poor conductors of heat compared to most solids.

**310. Do liquids conduct heat?** Let us put a piece of ice in the bottom of a testtube, weight it, and then fill the tube two thirds full of water. (See Fig. 346.) It is possible to boil the water at the top of the testtube for several minutes before the heat is conducted down the tube through the liquid to melt the ice. Water does conduct heat, but it is a poor conductor.

A still more sensitive test can be made by the use of the apparatus of Fig. 347. The bulb of an air thermometer is surrounded with water in a large funnel. The stem of the thermometer dips into some colored liquid. Ether is poured on the surface of the water and set on fire. Although the air thermometer is extremely sensitive, yet the liquid column is lowered only a little. This experiment, too, shows that water is a poor conductor. Other liquids, too, are poor conductors.

**311. Gases are very poor conductors.** It can be shown by experiment that gases are even poorer conductors of heat than liquids. Silver conducts heat more than 800 times as rapidly

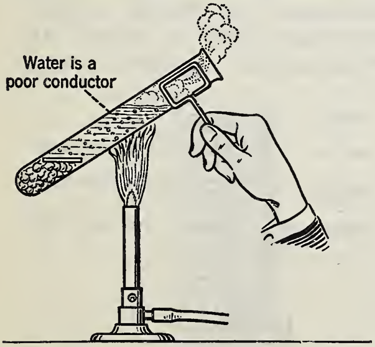

Water is a poor conductor

FIG. 346. Water is a poor conductor.

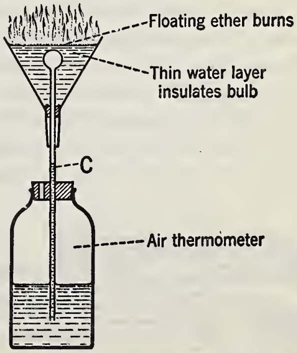


FIG. 347. An air thermometer is used to show that water is a poor conductor.

as water does, and almost 20,000 times as fast as air. Non-conducting layers of air in porous solids are largely responsible for their poor conductivity. A vacuum is a non-conductor of heat, or what is called a heat insulator.

**312. How does conductivity affect our temperature sense?** If we walk into the bathroom on a cold morning, we find that the tiled floor feels much colder than the rug which covers a part of the floor. A thermometer would show that both have the same temperature. The tiling feels colder than the rug because it is a better conductor of heat, and it *takes heat from* the foot faster than the rug does. A person who takes a pan of hot bread from an oven gets a more severe burn if he accidentally touches the metal pan than he does by touching the bread in the pan. Both have the same temperature, but the metal is a better conductor, and it transmits heat to the hand more rapidly. If both the pan and the bread were ice cold, then the pan would feel colder to the touch than the bread.

**313. How does clothing keep us warm?** The clothing which we wear does not afford us any warmth in winter, but it does prevent the heat of the body from escaping. That kind of clothing which is made of the poorest conducting material seems warmest. Wool and silk seem warmer than cotton and linen because they are poorer conductors. They help the body to retain its heat. Furs are very warm because they contain layers of non-conducting air. Two light garments are warmer than a single heavy one because there is a layer of air between them, and the air acts as an insulator. For the same reason, two light blankets are warmer than one heavy one.

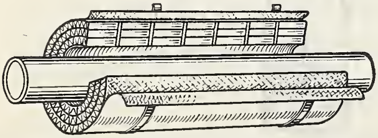


Fig. 348. Pipes are covered with heat insulators.

**314. How do we utilize conduction?** One portion of a stick of wood or lump of coal is heated until it is kindled. As it burns, the heat is conducted to other portions of the fuel, and they in turn begin to burn. Without conduction, fires would not spread along the various portions of a fuel so readily. Aluminum pans are much used for cooking utensils. The pan conducts the heat to the food which is to be cooked. The outer surfaces of the cylinders of rotary airplane engines and motorcycle engines are covered with deeply corrugated metal, sometimes copper. These projecting blades or fins help to carry away the engine heat and facilitate air cooling. The surface layers of the soil absorb the sun's heat, and some of this heat is conducted to the layers beneath.

**315. How can insulators be used to save heat?** Much money could be saved if more attention were given to insulation in the building of homes. The furnace itself is covered with "85% magnesia," a substance that is

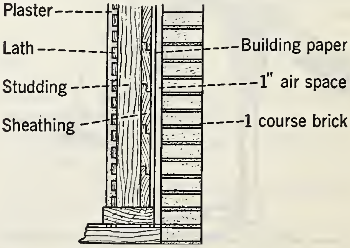
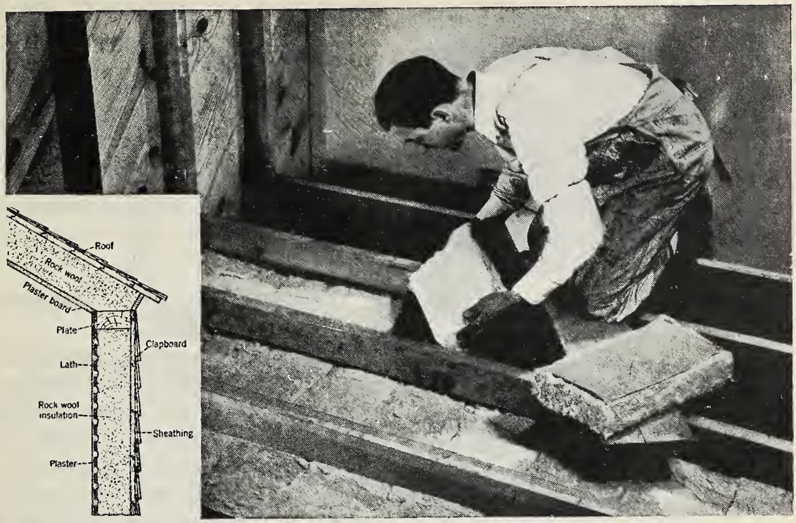


Fig. 349. Brick veneer walls and insulation.



*Courtesy of Johns-Manville Corporation*

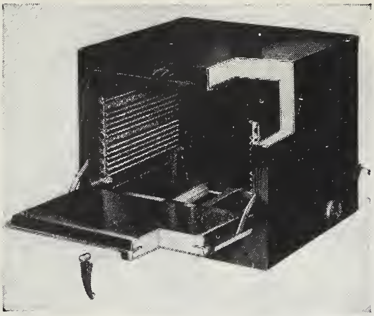
FIG. 350. Rock wool is used to insulate walls and roofs of houses.

extremely porous, or it may be covered with layers of corrugated asbestos, to keep the heat from escaping to the basement. The steampipes, too, in the basement and in the walls of the house may be covered with heat insulating material to prevent loss of heat before it reaches the rooms where it is wanted. (See Fig. 348.) Hot-water storage tanks have their walls insulated with rock wool. Houses are built with double walls and, in very cold climates, with double windows. The air spaces in the walls keep the heat from escaping in winter, and they keep the outside heat from coming in during the summer.

Brick-veneer houses are warm in winter and cool in summer if they are properly constructed. Let us refer to Fig. 349. The brick course must be kept about one inch from the sheathing to leave an insulating air space. A good building paper, or sometimes a kind of paper quilt is used to cover the sheathing. The space between the sheathing and the plaster is filled with rock wool or a light flaky mica called "zonolith," to help insulate the walls. The same material is used between the rafters. Thin sheets of aluminum foil under the name "Alfol" are also used to insulate roofs and walls of houses. (See Fig. 350.)

**316. How do modern gas ranges save heat?** Many so-called "fireless" gas and electric ranges are now constructed with the idea of conserving heat. The oven in such a range is made with double walls, and the space between the walls is filled with mineral wool or some other heat insulator. (See Fig. 351.) When a roast is put in such an oven, the gas is lighted and kept burning for 30 or 40 minutes. Then it is turned off and the oven sealed. The heat absorbed by the walls of the oven is sufficient to finish the cooking of the roast.

A kind of well is used for cooking vegetables by boiling. The walls of this



Courtesy of the Chambers Corporation

FIG. 351. The oven of some gas ranges has walls made of insulating material.

well are heated while the gas flame is being used to bring the water up to boiling, or for the first 10 minutes of the cooking. They absorb enough heat to complete the cooking of the vegetables after the gas is turned off. (See Fig. 352.)

**317. The thermos bottle conserves heat.** Hot liquids poured into a thermos bottle stay hot a long time, and cold liquids stay cold. This bottle utilizes the fact that a vacuum is a non-conductor of heat. Such bottles are generally made of glass so blown that the walls will be double, as in Fig. 353. The air is then exhausted from the space between the walls, and the bottle is sealed so that no air can then get in. Heat does not pass through the walls by conduction, and the walls are silvered to prevent the transmission of radiant heat.

Courtesy of the Chambers Corporation

FIG. 352. The walls of the well absorb heat and finish the cooking of vegetables.

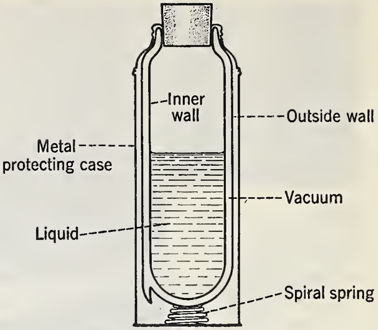


FIG. 353. The thermos bottle depends upon the insulating qualities of a vacuum.

Some large thermos bottles are mounted on motor trucks. Dairymen chill the milk by letting it flow in thin layers over coils containing cold brine and then pour it into the huge thermos bottles to keep it cold during shipment.

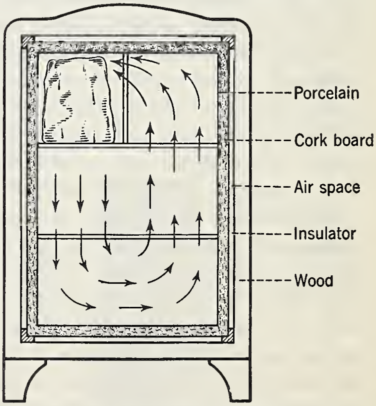


FIG. 354. A refrigerator is as good as the insulating material in its walls.

**318. The refrigerator is a heat insulator.** The old saying, "What will keep out cold will keep out heat," is a true one. Our refrigerators are built with this idea in mind. A good refrigerator box has double or triple walls. The space between the walls is filled with such insulating material as corkboard or mineral wool. The door must close tightly and be kept closed as much as possible. The melting ice chills the food. (See Fig. 354.)

## 2. Convection

**319. What is the principle of convection?** Suppose that we add a few particles of sawdust to a beaker nearly full of water and heat it near one edge as shown in Fig. 355. The water directly over the flame expands and becomes less dense. The heavier water from the opposite side of the beaker flows across and pushes up the lighter water, thus setting up *convection currents* as shown by the arrows. The circulatory movement of the water is shown by the motion of the sawdust particles.

If we light a heater in the center of a large room, the air over the heater will expand. This lighter air is pushed upward by the colder, heavier air flowing in along the floor toward the center of the room. As the warm air reaches the ceiling, it spreads out toward the walls, sinking downward again as it cools. *Convection currents* may be set up in either liquids or gases by unequal heating. By means of such currents, heat is *transmitted by the movement of the heated masses.*

**320. How shall we ventilate?** The whole plan of ordinary ventilation depends upon convection. The air which we exhale is warmer and lighter than out-of-door air. The foul air may be pushed out of an open window near the top of a room by the fresh air which enters nearer the floor. The three diagrams of Fig. 356 show clearly how convection currents are useful in ven-

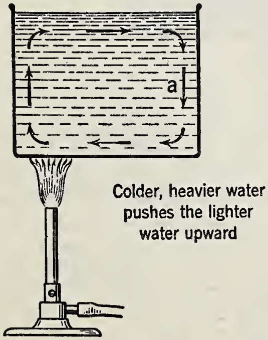


FIG. 355. Convection currents in liquids.

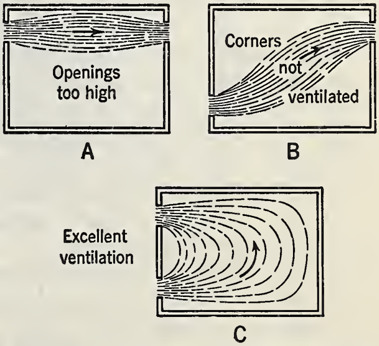


FIG. 356. A room should have cross-ventilation, without direct draft.

tilating rooms. For ventilating large buildings and mines, compressed air is in common use.

**321. What is air conditioning?** The average adult eats about a ton of food every year, but during the same time he breathes more than six tons of air. We wrap our foods in cellophane, and we hire inspectors to test the purity of our foods, but relatively little attention is given to the proper conditioning of air.

The engineer has found that at least four things need to be done in the proper conditioning of air if one is to be comfortable, efficient, and healthy.

1. The air must be warmed in winter and cooled in summer. Man can adapt himself to extremes of temperature, but he works most efficiently when the temperature range is from 63° F. to 75° F.

2. The relative humidity should not be less than 30%, nor more than 70%, preferably between 40% and 60%. One often hears the expression, "It isn't the heat, but the humidity." (See Fig. 357.)

3. Air should be filtered to remove particles of dust and bacteria that are always present in air to some degree. The accumulation of dust particles in the lungs is responsible for diseases of these organs.

4. The air must be kept in constant, gentle motion.

Air-conditioning units are available for hotels, trains, office buildings, schools, and homes. In such units, the air is filtered. It is warmed in winter and cooled in summer. Moisture is removed from the air when it is present in excess, and the air is moistened when it is too dry. A fan is driven by an electric motor to keep the air in motion. The expense of installing and operating air-conditioning units is the only thing that keeps them from becoming very popular. (See Fig. 358.)

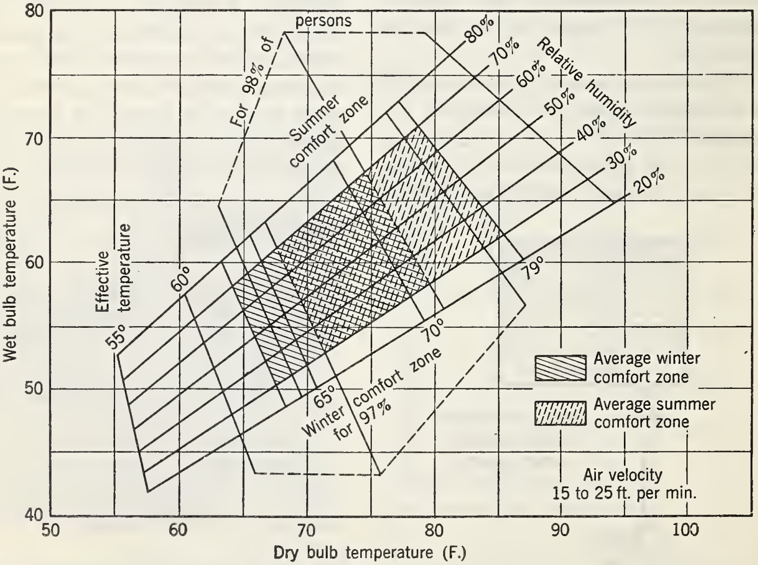
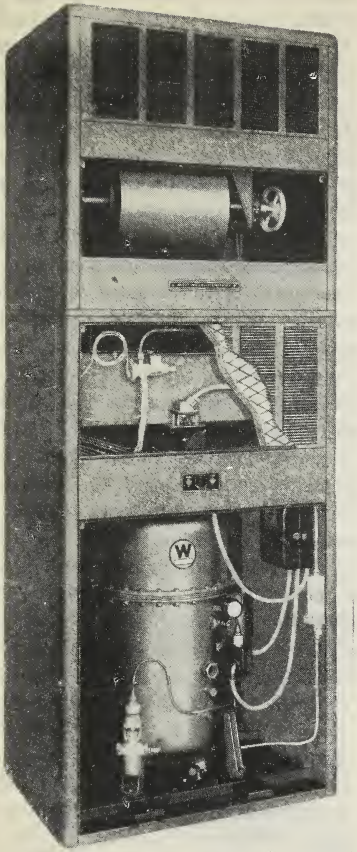


FIG. 357. The chart shows the air conditions that are conducive to comfort.



Courtesy of Westinghouse

FIG. 358. Independent air-conditioning unit.

**322. Why does a chimney draw?** We know that a chimney draws when the wind blows across the top because of Bernouilli's principle. But even on a calm day there is an upward draft in a chimney. Before the fire is started in the furnace or stove, the air inside the chimney has the same density as the air outside. But when the fire is started, the air above it expands. Colder, heavier air from outside then pushes the warm air up the chimney and also the hot waste products formed by combustion.

FIG. 359. This tall stack, built for smelting copper ores in Montana, is so large that the Washington Monument would disappear from view if placed inside. Its height is 583 ft.

A tall chimney draws better than a short one, because there is a greater difference in weight between the hot gases inside the chimney and an equal volume of cold air outside. (See Fig. 359.)

**323. What causes winds?** The unequal heating of the air at different places on the earth's surface causes huge convection currents in the atmosphere. In this way winds are caused. Let us study some of them in greater detail:

1. *Land and sea breezes.* For several reasons, water in the oceans heats more slowly than the land along the shore. It has a higher specific heat than the land; it is transparent, allowing the sun's heat rays to penetrate to greater

depth; and it is in more or less constant motion. Hence, by the middle of the forenoon on a sunny day, the land area, and also the air above such an area, will be more highly heated. The colder, heavier air from the ocean blows in and forces the lighter air upward. Along the coast, a *sea breeze* comes up in the middle of the forenoon and blows steadily until late evening. (See. Fig. 360.)

At night, the land cools more quickly than the water, and the air over the ocean becomes warmer than it is over the land. A *land breeze* then blows toward the ocean, usually beginning shortly before midnight. Fishermen along the coast use the land breeze to go to sea at night; they return in the forenoon with the sea breeze.

2. *Monsoons*. These winds are like land and sea breezes, but they are *seasonal*. In some localities, the land areas are so intensely heated in *summer* that the wind blows continually toward the land for a period of about five months. After about one month of more or less variable winds, a huge land breeze blows toward the warmer ocean during the *winter* season.

3. *The trade winds*. The direct rays of the sun in the vicinity of the equator, in March or September for example, heat the equatorial areas strongly and produce upward air currents. Where the air is being pushed upward, there is no lateral movement of air, but a calm belt known as the *equatorial calm belt,* or the "doldrums." Colder, heavier air blows toward the equator from both the north and the south. These *trade winds* blow continually throughout the year. We would expect the trade wind south of the equator to blow due north and the one north of the equator to blow due south, but the rotation of the earth on its axis deflects them. In the southern hemisphere we have the *southeast trades*, and in the northern hemisphere the *northeast trades*. (See Fig. 361.) The student should note from the arrows that the warm air over the equator is being pushed upward by the colder air of the trades drifting toward the equator. There are abnormally high pressure areas over the Tropics of Cancer and Capricorn. The air currents there are descending. For that reason we have the *Calms of Cancer and Capricorn* known to sailors as the "horse latitudes." Fig. 361 shows the general atmospheric circulation in the spring and fall. During our summer, the calm belts and the trade winds shift northward. In the winter they shift southward.

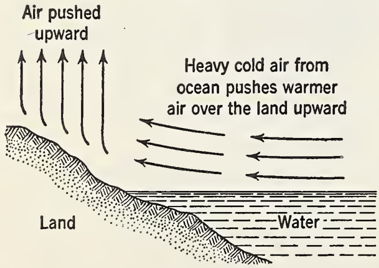

Air pushed upward
Heavy cold air from ocean pushes warmer air over the land upward
Land
Water

Fig. 360. Sea breezes blow toward the land during the day.

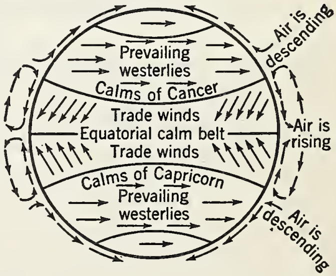


Fig. 361. This chart shows atmospheric circulation when direct rays of the sun shine on the equator.

**324. There are several different heating systems.** 1. *Hot-air.* In *hot-air* heating systems, the heat is distributed by convection currents. The cold air usually enters from out-of-doors directly, Fig. 362, circulates around the firebox, and then rises to the rooms. A part of the air then escapes through doors and windows, while in some systems a part returns to the furnace, where it is mixed with fresh air and reheated.

Some hot-air furnaces now in use are *pipeless.* Such furnaces depend entirely on convection currents to distribute the heat to all parts of the house. The furnace of Fig. 363 has one large register directly over the furnace. The hot air rises from the center of the register, circulates through the rooms by way of transoms and doors, and returns to the furnace to be reheated. The register is composite, having an opening in the center for the heated air, and an annular opening surrounding the former through which the air is returned for reheating.

2. *Hot-water.* In some houses, *hot-water* heating systems are installed. The principle is the same as that used in hot-air systems, but in this case water is warmed and convection currents are set up in the water. The water which circulates around the firebox is heated and rises to the radiators. Here it loses heat to the room by radiation, and then returns to the bottom of the furnace to be reheated.

In such a system, the radiators must be larger than those used with steam-heating systems, since the water is not heated to boiling. Generally, it is not heated to more than 160° F. in cold weather, and much less in mild winter weather. Two pipes must be used, one for the entrance of the hot water, and the other as a return pipe. An expansion tank is always connected with the system to accommodate the increased volume which the water occupies when heated, and also to act as a safeguard for the escape of steam if the water should boil. The arrows of Fig. 364 show the direction of the circulation

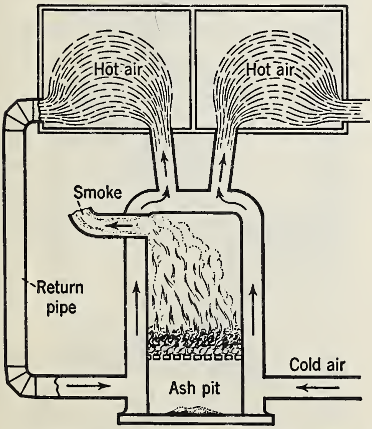


FIG. 362. Hot-air heating system shows air circulating by convection.

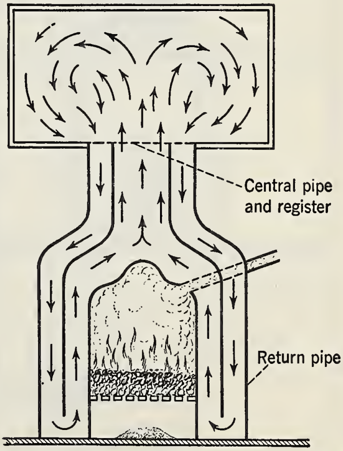


FIG. 363. The pipeless hot-air furnace is used in cottages and small houses.

of the water by means of convection currents. In the room, convection currents are set up in the air, since the air above the radiator is warmed. Thus the heat is transferred to the room.

3. *Steam-heat.* In *steam-heating* systems, the water is heated to boiling, and the steam, which occupies several hundred times as much volume as the water had occupied, expands through the pipes and into the radiators. As the steam condenses in the radiators, each gram sets free 540 calories of heat; or each pound liberates 972 B.T.U.'s. This heat is utilized in warming the room. The heat from the radiator is distributed to the room by convection and by radiation. After condensation occurs, the water returns to the boiler, usually through the same pipe. (See Fig. 365.) In large buildings, where the volume of water formed by condensation is greater, a separate pipe is used as the return pipe. Fig. 366 shows the arrangement of furnace and radiators in a steam-heating system.

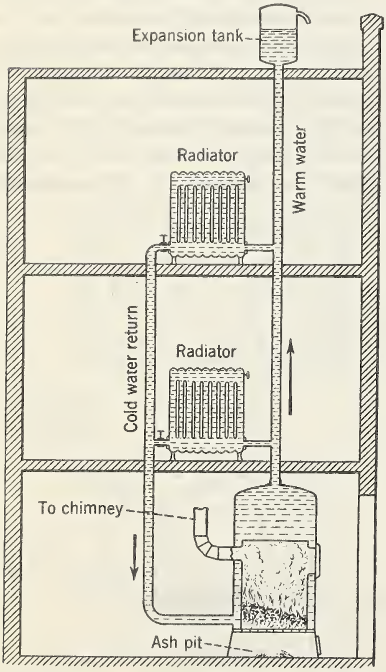


FIG. 364. Diagram to show method of heating by hot water.

4. *Vapor-heat.* The *vapor-heating* system uses the same type of boiler that is used in the steam-heating system. We know that water boils at a lower temperature under reduced pressure. In the *vapor* system, some method is used to get rid of part of the air in the pipes and radiators. This may be done by means of a pump or by use of the ejector principle. Of course, two pipes must be used in such a system, and the radiators and connecting pipes must be kept gas-tight. If the pressure inside such a system is reduced to one half an atmosphere, the water will boil at about 180° F.

**325. How do heating systems compare?** 1. The hot-air system is less expensive to install. It is easily controlled in mild weather, when little

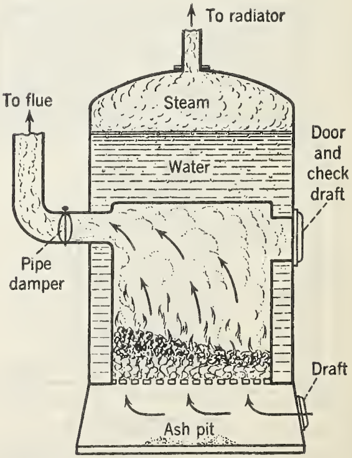


FIG. 365. A steam-heating furnace.

heat is needed. There are no unsightly radiators. However, dust and dirt get into the house more readily from the cold air inlet. It is sometimes difficult to heat the rooms on the windward side of the house. In severe weather, the system is considered less efficient than other systems.

2. Steam-heating systems are less expensive to install than hot-water and vapor systems. They are efficient in cold weather, especially in large buildings where pressure boilers are used. On the other hand, such a system is hard to control in the spring and fall when only a little heat is needed. The house cools off quickly when the fire is banked at night. The radiators take up room and are generally inartistic.

3. For use in the spring and fall, the hot-water heating system is almost ideal. The water may be kept at a temperature just sufficient to keep the house from becoming chilly. Such a system is also satisfactory and efficient in cold weather. The hot-water heating system is more expensive to install, since return pipes must be used and the radiators are larger. The circulation is sometimes sluggish. If the owner were careless, of course, a freeze would crack radiators, pipes, and furnace.

4. The vapor-heating system combines the advantages of the steam and hot-water heating systems. It is efficient and easily controlled in all kinds of weather. The radiators are larger than those used for steam but smaller than those used with hot water. Unfortunately, this system is more expensive to install than any of the other systems.

**326. How does the hot-water tank work?** The method of heating water for

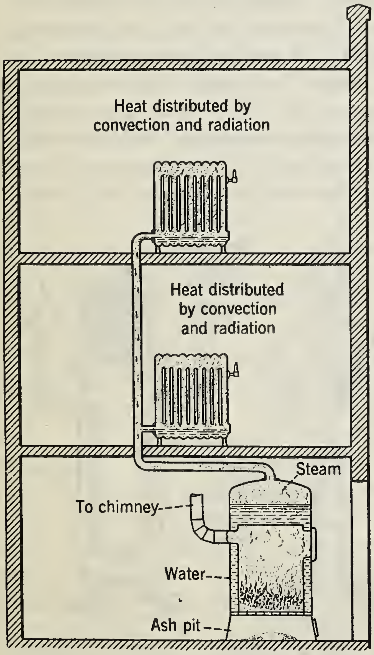

Heat distributed by convection and radiation
Heat distributed by convection and radiation
Steam
To chimney
Water
Ash pit

Fig. 366. A steam-heating system to show heat distribution

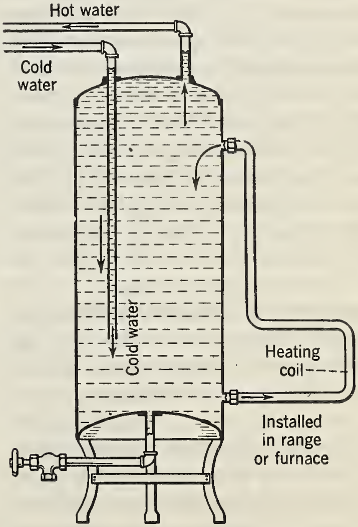

Hot water
Cold water
Cold water
Heating coil
Installed in range or furnace

Fig. 367. The hot-water tank. An example of convection.

the kitchen, bath, or laundry does not differ much from the hot-water system of heating houses. A heating coil is placed in the furnace, or just outside, so that steam flows around it. Quite often gas is used to heat the water in the coil. As this water is heated and expands, it is pushed up to the top of the storage tank by the colder, heavier water which enters near the bottom of the tank. (See Fig. 367.) When hot water is drawn off from the top of the tank, more cold water enters from the pipe near the bottom. Convection currents are set up in the direction shown by the arrows.

## 3. Radiation

**327. What is radiation?** When the hand is held in front of a fireplace, it is quickly warmed by radiation. In the same manner we receive heat from the sun. Since heat is a form of energy produced by the motion of the molecules, waves are set up in the surrounding medium. Huygens advanced the wave theory to account for the transmission of radiant energy. Radiations travel through a vacuum; so he presupposed the existence of a very subtle medium which pervades all space and transmits radiant energy. This medium is called *ether*. It is supposed to be an invisible fluid, so very rare that it cannot be weighed or measured; it easily penetrates intermolecular spaces. *The absorption of radiant energy produces heat in the absorbing medium. Substances easily penetrated by the ether waves are little warmed by their passage.*

**328. Heat is absorbed, reflected, or radiated.** When heat waves are incident upon an object, a part are reflected, part may be transmitted, and the rest are absorbed. Polished metals are the best reflectors known; hence they are very poor absorbers of heat. A poor absorber of heat is also a poor radiator. A roughened teakettle absorbs heat more readily than a highly polished one; it also loses heat faster by radiation.

The color of a substance also affects its absorbing power. A black surface absorbs heat faster than a white one. Hence, light-colored garments are cooler in summer sunshine than black ones. Lampblack is the best absorber known and also the best radiator.

Crookes' radiometer may be used to demonstrate these facts. It consists of a partially exhausted bulb, in which is suspended a light aluminum wheel that has a set of vanes in its circum-

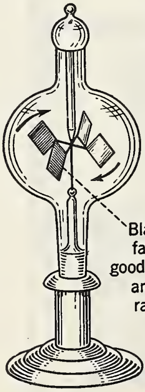


Fig. 368. A Crookes' radiometer operates in sunlight.

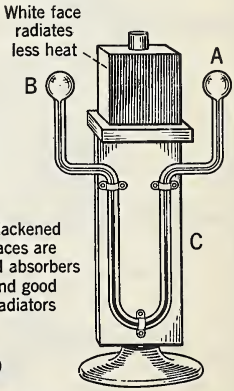


Fig. 369. Leslie's cube and a differential thermometer.

ference. Each vane is polished on one side and covered with lampblack on the other. When exposed to a source of radiant energy, heat is absorbed more rapidly by the black surfaces. The adjacent air is more highly heated and rebounds with a greater velocity from the black surfaces, thus exerting greater pressure and causing the wheel to rotate in the direction shown in Fig. 368.

By the use of Leslie's cube and a *differential* thermometer, Fig. 369, it may also be shown that a black surface radiates heat faster than a white one. Surfaces of the cube are painted different colors. It is filled with hot water and supported so that the black face will be the same distance from bulb *A* of the thermometer that the white face is from bulb *B*. Since bulb *A* is heated more rapidly by radiation from the black surface, the air within this bulb expands more and forces the liquid *C* down the tube.

**329. What are the laws of radiation?** When the moon comes between the sun and the earth during an eclipse of the sun, it cuts off both the heat rays and the light rays at the same time. Since light is known to travel at a velocity of more than 186,000 miles per second, we conclude that heat waves travel at the same velocity. Heat waves also travel in straight lines.

A person sitting near a fireplace receives more heat than one who is farther away. The higher the temperature of a radiator, the more heat waves it gives off by radiation. Measurements show that the *intensity of radiant energy is directly proportional to the temperature of the source, and inversely proportional to the square of the distance.* The planet Mercury is only about one third as far from the sun as the earth; hence it must receive about nine times as much radiant heat as the earth receives.

Suppose we put two cups of warm water in a refrigerator to cool. The refrigerator has a temperature of 50° F.; one cup of water has a temperature of 60° F., and the temperature of the other is 70° F. By the use of a thermometer it may be shown that the latter cools twice as fast as the former. It is 20° warmer than the refrigerator and the former is only 10° warmer. NEWTON'S LAW OF COOLING may be stated as follows: *The rate of cooling by radiation is proportional to the difference between the temperature of the cooling body and the surrounding medium.* A house at 60° F. cools off twice as fast when the outside air is 20° F. as it does when the temperature is 40° F.

**330. What is heat transparency?** When the ether waves produced by radiant energy pass through a substance without heating it, then the substance is said to be *diathermanous.* Substances opaque to heat are *athermanous.* Dry air is quite transparent to heat, but air containing much water vapor is much more opaque. Clouds absorb heat as it travels from the sun to the earth, and they prevent, to a great extent, the loss of heat from the earth by radiation. On high mountains the sun's heat is intense.

Some substances are transparent to light, but opaque to heat. Alum is an example. Conversely, iodine solution is opaque to light, but transparent to heat.

Heat from the sun readily comes in through glass windows, but heat from the radiators does not pass out through glass readily. If the temperature of the source of heat is very high, its waves are short and very penetrating. The heat waves given off from a radiator are long waves and much less penetrating. Glass is used for covering greenhouses and "cold frames"; the heat from the sun passes in through the glass, but there is little loss by radiation.

## Summary

Heat may be transmitted by conduction, convection, and radiation. Solids conduct heat better than liquids or gases. Convection does not occur in solids.

Good conductors feel hotter than they really are, if their temperature is higher than that of the hand; when their temperature is lower than the hand, they feel colder.

Heat insulation is extensively used in house construction, building refrigerators, covering pipes, and in fireless ranges.

Convection depends upon the fact that fluids expand when heated. Ventilation systems, hot-air and hot-water heating systems, and atmospheric circulation all depend upon convection currents.

Good absorbers of heat are good radiators. Good reflectors are poor absorbers and poor radiators.

*How many of the following terms and phrases can you define or explain? (Try first. Check afterwards.)*

Conduction in solids
Fireless ranges
Gases as insulators
Thermos bottle
Ventilation
Principle of convection
Winds, cause of
Trade winds
Heating systems
Insulators as heat savers
Refrigerators
Air conditioning
Land and sea breezes
Monsoons
Hot-water tank
Radiation of heat
Absorption of heat
Laws of radiation

## QUESTIONS

1. Why does wrapping ice in a woolen blanket keep it from melting rapidly? Is ice of much value in a refrigerator unless it melts? Explain.

2. Why does a chimney "draw"? How does the height of the chimney affect the draft? Why does a chimney "draw" better on a clear, cold day than in damp, cloudy weather? Explain why a chimney "smokes" when a new fire is started.

3. Why are houses built with hollow walls?

4. Why do stove lifters and pokers usually have wooden or coiled wire handles?

5. Why do workmen around furnaces wear woolen clothing even in summer?

6. Does clothing supply us any heat in winter? How does it keep the body warm?

7. How does snow protect the grass in winter?

8. In making ice cream, why is the cream usually put in a metal container and the ice in a wooden vessel?

9. Is it economy to keep stoves highly polished? Explain.

10. Why does dew or frost seldom form on cloudy nights?

11. On high mountains the sun is exceedingly hot in the daytime, but the temperature usually falls below freezing at night. Explain.

12. Why does it rain nearly every afternoon in the equatorial regions?

13. Why is it necessary for a radiator to have more sections when used with hot water than with steam heat?

14. Does tea cool more quickly in a tarnished metal pot or in a highly polished one?

15. Which is warmer, cotton or linen clothing? Why?

16. Why does mist often form in the receiver of an air pump?

17. Since solids are better conductors of heat than gases, why does packing rock wool in the walls of houses or between the rafters help to insulate a house?

18. Why is silvered glass used in making thermos bottles?

19. Two pieces of cloth are laid upon the snow. One of them is black; the other, white. The black one sinks into the snow faster on a sunshiny day. Why? If we cover the black one with powdered alum and the white one with powdered iodine, the condition will be reversed. Explain.

20. In what way do double windows save fuel?

21. Why are steampipes in the basement covered with asbestos or magnesia?

22. Why does the tongue or a moistened finger freeze to a cold metal, but not to wood of the same temperature?

23. Is it economical to have steam radiators highly polished? Would it be economical to have them painted black?

24. How does heat get from the radiators to the various parts of a room?

25. Make a list of at least six heat insulators used in a dwelling house.

26. At the tropics, air currents are descending. Account for the arid regions there.

# *Heat and Work*

**331. Heat and work are related.** We rub our hands to warm them. We not only stimulate circulation, but the friction, which is *wasted work*, is transformed into heat. A carpenter finds that his saw is heated by friction when he uses it for some time. Impact also produces heat, since it produces *internal* friction between the molecules. The heat of impact may be sufficient to melt a bullet fired against a hard target.

James Prescott Joule, the English physicist who stated the law of the conservation of energy, devised an apparatus for use in finding out how much work must be done to produce one British thermal unit of heat. The apparatus was designed to waste 100% of the energy put into it. (See Fig. 370.) In this apparatus, weights are permitted to fall a certain distance. In falling, the weights merely turn a set of paddles immersed in a known weight of water. The constant paddling of the water warms it by friction.

By multiplying the weight used by the distance it falls, one can easily calculate the number of foot-pounds of work wasted during the experiment. By multiplying the weight of water by the number of degrees Fahrenheit its temperature was raised during the experiment, one can calculate the number of British thermal units of heat produced by the wasted work. Joule found that it takes 772 ft.-lb. of work to produce one B.T.U. of heat. The average of a large number of experiments, more recently performed, shows that *778 ft.-lb. of work are equivalent to one British thermal unit of heat.* In the metric system, *427 gram-meters of work are equivalent to one calorie.* In terms of work, the calorie may be defined as $4.19 \times 10^7$ ergs, or 4.19 joules.

**332. How is heat converted into work?** It seems to be a poor rule that will not work both ways. If it is possi-

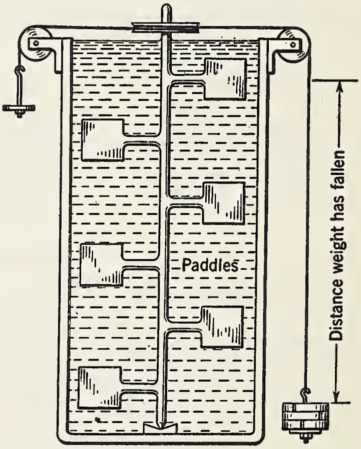


Fig. 370. An instrument designed to change all its energy into heat energy.

---

## Vocabulary

MECHANICAL EQUIVALENT, the value of heat units in terms of work units, or vice versa.

RECIPROCATING, to and fro.

TURBINE, a rotary motor driven by water or steam.

STATOR, the stationary case or base of a turbine.

ROTOR, the rotating part of a turbine.

CARBURETOR, a device for vaporizing gasoline and mixing the vapor with air.

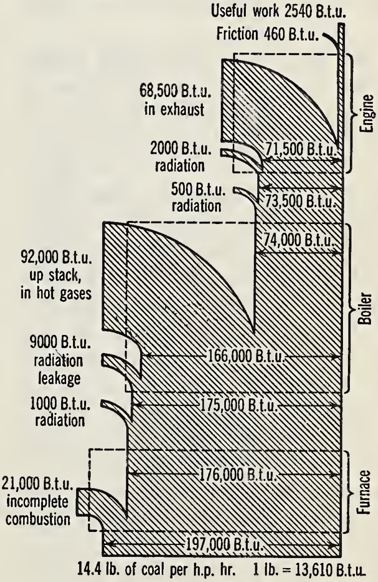
ble to waste work and produce heat, then it seems reasonable to believe that it is possible to use heat energy to do work. It is possible to do this in several ways. It can be shown by experiment that *one British thermal unit of heat can do 778 ft.-lb. of work,* and that *one calorie can do 427 gram-meters of work.* These numbers are called *the mechanical equivalents of heat.* Let us mention briefly some of the methods used to make heat do work for us:

1. *In our own bodies.* Biologists tell us that a thick slice of bread, when oxidized, furnishes *100 large Calories* or *100,000 small calories of heat.* Suppose that the bread is oxidized in your body and all converted into muscular energy. It is then capable of doing 42,700,000 gm.-m. of work. At an efficiency of 100%, that heat energy would enable you to climb a mountain almost 2500 ft. high, if your weight is 125 lb. Of course, part of the heat energy which we derive from our food is used to keep the body temperature at 98.6° F., summer or winter. Some of our food is utilized for nutrition and repair. Experiments carried out by Professor Atwater of Wesleyan University showed that only 28% of the heat energy of a man's food was converted into muscular energy.

2. *By use of steam.* When water is converted into steam, it expands about 1700 times and exerts pressure in all directions. In a steam boiler, the steam is confined until it reaches a high pressure. From the boiler it is led to the cylinder of a steam engine, where it expands and pushes a piston back and forth in the cylinder, thus doing work. Heat energy from the burning coal or oil produces the steam, and the steam in expanding produces the mechanical energy as it drives the piston to and fro.

Suppose that a pound of coal furnishes 14,500 B.T.U.'s. If all this heat is converted into work, one pound of coal is equivalent to 14,500 × 778 ft.-lb., or 11,281,000 ft.-lb. of work. For every pound of coal that is burned per hour, the engine should develop $\frac{11,281,000}{550 \times 60 \times 60}$ H.P. That is about 5.7 H.P. continuously. In practice, the ordinary steam engine uses about 1.5 lb. of coal to produce 1 H.P. per hour, an efficiency of about 11%. Some of the most efficient steam engines do not have an efficiency much above 20%.

Such low efficiency is not astonishing if we consider that nearly 30% of the heat energy goes up the chimney during combustion. About 50% of what


Useful work 2540 B.t.u.
Friction 460 B.t.u.
68,500 B.t.u. in exhaust
2000 B.t.u. radiation
71,500 B.t.u.
500 B.t.u. radiation
73,500 B.t.u.
74,000 B.t.u.
Engine
92,000 B.t.u. up stack, in hot gases
9000 B.t.u. radiation leakage
166,000 B.t.u.
1000 B.t.u. radiation
175,000 B.t.u.
Boiler
21,000 B.t.u. incomplete combustion
176,000 B.t.u.
Furnace
197,000 B.t.u.
14.4 lb. of coal per h.p. hr. 1 lb. = 13,610 B.t.u.

*Courtesy of J. A. Randall*

FIG. 371. Diagram to show how heat energy is distributed in a furnace, boiler, and engine.

remains is lost because it is impossible to use all the expansive force of the steam. The energy diagram of Fig. 371 shows how the heat energy from a burning fuel is used or wasted in a power plant.

3. *In internal combustion engines.* In steam engines the fuel is burned beneath the boilers to produce steam. Such an engine is an *external combustion engine*. In gasoline engines, the fuel is burned inside the cylinders. They are examples of *internal combustion engines.* A carburetor is used to vaporize the gasoline and mix it with air so that it will explode. The mixture of gasoline vapor and air is exploded in a thick-walled cylinder, usually by means of an electric spark. The heat energy from such explosions causes the gaseous products formed by the explosions to expand and push against the piston with great force.

**333. How does the steam engine work?** From the boiler the steam is led to the steam chest through the pipe *E*, Fig. 372. When the slide valve is in the position shown in the figure, the steam passes from the steam chest into the right end of the cylinder. Here it expands and pushes the piston with great force toward the left end of the cylinder. The spent steam from the previous stroke passes from the left end of the cylinder and out through the exhaust pipe. The path of the expanding steam is shown by the arrows.

The valve then slides to the right until the left end of the cylinder is connected with the steam chest, and the right end with the exhaust pipe. Steam enters the left end of the cylinder and pushes the piston to the right. By the movement of the valve, steam is admitted alternately to the ends of the cylinder. Thus the piston is pushed to and fro alternately. Such a motion is called a *reciprocating* motion. The student should observe that the openings in the cylinder are connected alternately with the steam chest and the exhaust by means of the sliding valve.

**334. How does the piston turn the drive wheel or the belt wheel?** The motion of the piston is reciprocating, or to-and-fro. If it is to drive the wheels of a locomotive or turn the belt wheel of a piece of machinery, it is necessary to change the to-and-fro motion into a rotary one. (See Section 232 on the treadle of the sewing machine.) In Fig. 373, one end of the piston rod, *A*, is fastened to the end of the shaft, *S*. The other end of this shaft is attached to the crankpin, *F*, at the end of the crank, *FO*, by means of a collar. While the piston in the cylinder (not shown in figure) moves to the right the length of the cylinder, the point *E* moves to the right a distance equal to the diameter, *CD*, of the circle described by the crankpin, *F*. Of course, the crankpin moves along the half-circumference from *C* to *D*. During the return stroke of the piston, the point *E* moves to the left and pulls the crankpin, *F*,

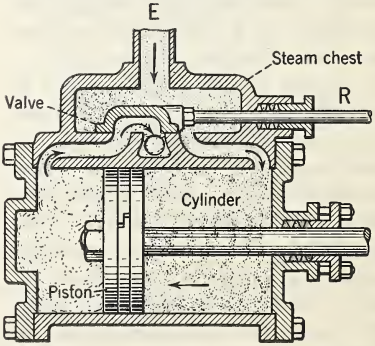


Fig. 372. Steam-engine cylinder and steam chest with slide valve.

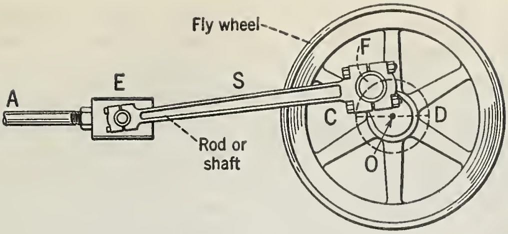


FIG. 373. Reciprocating motion is changed to rotary motion.

around the other half-circumference from $D$ to $C$. The inertia of the heavy flywheel carries the piston past the two points where there is no steam pressure, or past the two positions known as "dead centers."

**335. How are the valves controlled?** 1. *Slide valves.* It is important to remember that the slide valve must open and close the pipes leading from the steam chest to the different ends of the cylinder at exactly the right time. They make connections, too, between the ends of the cylinder and the exhaust pipe. The rod $R$ of Fig. 372 is connected by means of shaft $A$, Fig. 374, to an eccentric controlled by the crankshaft upon which the flywheel turns. The shaft, $A$, ends in a collar which fits around the disc, $D$. This disc rotates about the center, $C$, an axis which is off center (eccentric). During one half a revolution, the point $X$ moves along the curve as indicated by the arrows, and the end, $A$, of the shaft or rod moves to the left and slides the valve to the left in the steam chest. As the revolution is completed, the end of the shaft is pulled an equal distance to the right. While the point $X$ describes a complete circle, point $A$ moves backward and forward, controlling the movement of the valve at the same time.

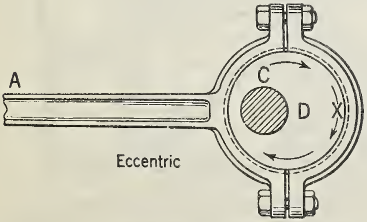


FIG. 374. An eccentric is used to control a slide valve.

★2. *Corliss valves.* These valves, which are used in some large steam engines, do not slide back and forth, but they open and close by rocking or turning slightly in the valve seats. (See Fig. 375.) Each of the four valves may be timed independently of the others, thus making greater efficiency possible.

**★336. There are two types of steam engines.** 1. *Non-condensing engines.* Suppose the steam as it comes from the steam chest into the cylinder is under a pressure of 85 lb. per sq. in. It presses against every square inch of the piston with that force as it pushes the piston along the cylinder. But the spent steam on the opposite side of the piston is meeting a backward pressure of one atmosphere, or nearly 15 lb. per sq. in., as it is escaping into the air. Such back pressure reduces the *effective steam pressure* to only 70 lb. per sq. in. To get an effective pressure of 85 lb. per sq. in. with such an engine, the pressure in the steam chest must be equal to 100 lb. per sq. in. A steam engine of

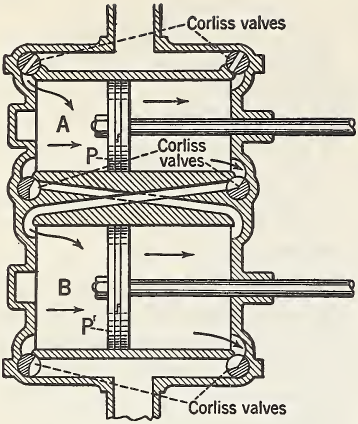


Fig. 375. A double-expansion engine.

this type is called a *high-pressure engine* or a *non-condensing engine.*

2. *Condensing engines.* Many stationary engines are fitted with a condenser, in which the spent steam is condensed by means of a spray of cold water. Thus a partial vacuum is formed in the condenser, and the backward pressure of the air against the escaping steam is much reduced, possibly to only 1 lb. per sq. in. If an engine is fitted with such a condenser, a boiler pressure of 86 lb. per sq. in. is approximately as effective as a boiler pressure of 100 lb. per sq. in. when used with a non-condensing engine. *Condensing engines* are sometimes called *low-pressure engines.* Of course, a condenser adds to the weight of the engine.

**★337. What is a compound engine?** Many locomotive engines are of the high-pressure, non-condensing type. To increase efficiency, *compound engines* are used. (See Fig. 375.) When the steam leaves the first cylinder, it still has much expansive force. Hence it is led to a second cylinder, where it does useful work by expanding against a larger piston, $P'$. An engine of this

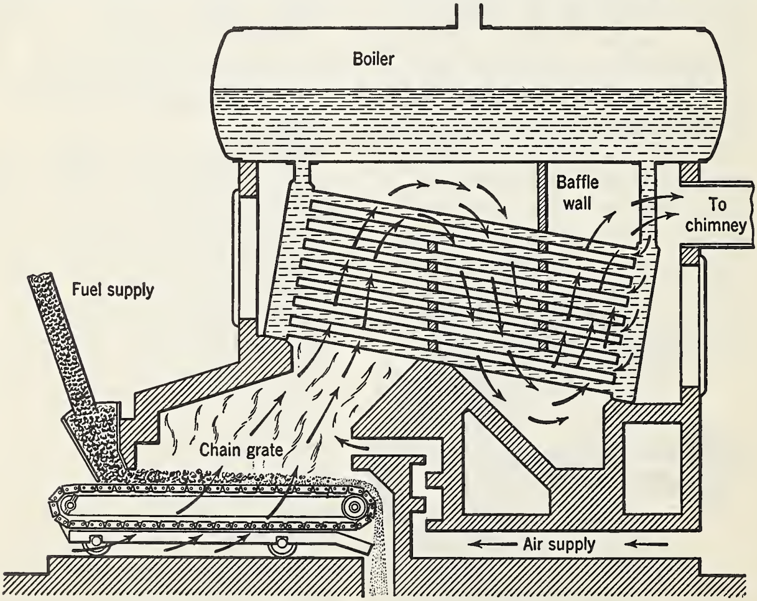


Fig. 376. The automatic stoker saves fuel and eliminates smoke.

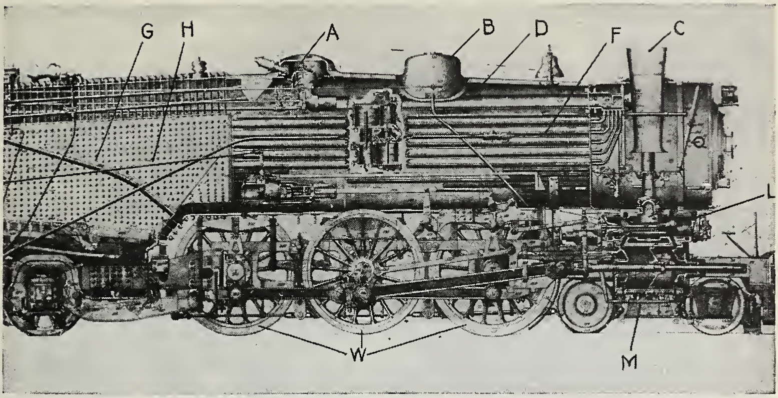


FIG. 377. Locomotive diagram. A. Throttle. B. Sandbox. C. Smokestack. D. Steam pipe. F. Flue, or boiler tube. G. Sectional brick arch, to protect flues. H. Reverse gear rod. L. Piston valve. M. Piston in cylinder. W. Drive wheels.

From the diagram, it is evident that most of the weight of the locomotive rests on the drive wheels. This enables the wheels to grip the track more firmly, but still the drive wheels of a locomotive sometimes spin around rapidly when the latter is attempting to start a heavy train. Can you explain this? What is the purpose of the sandbox on a locomotive?

type is called a *double-expansion engine*. *Triple-expansion* and even *quadruple-expansion engines* are sometimes used.

**338. How is boiler efficiency provided?** An ordinary wash boiler heated over a gas range produces steam, but the volume of steam produced is very low because there is so little surface exposed to the flame compared to the volume of water. The manufacturer of boilers for generating steam so designs them that the fire and flames will come into contact with the largest possible heating surface. Two types are in use:

1. *Water-tube type.* Such a boiler is often used with stationary engines. The flames play all around a number of pipes filled with water and also against the bottom of the boiler itself. (See Fig. 376.) More heat is absorbed in this way. Some automatic stokers are of the underfeed type and some are an endless screw.

2. *Fire-tube type.* This type of boiler is used on locomotives. From the firebox the flames are drawn through long horizontal tubes which are surrounded with water. The exhaust steam escapes through the smokestack and produces the draft. (See Fig. 377.) In forested regions destructive fires have been caused by sparks escaping from the stack.

**339. How do engineers save fuel?** In the diagram of Fig. 376 we see that *baffle walls* are used to prevent the flames and hot gases from going directly up the chimney. They are forced to take a circuitous path which enables the water to absorb more of the heat before they reach the stack. The automatic stoker feeds the coal to the fuel just as fast as it is burned, thus insuring complete combustion. An additional supply of hot air is fed into the flames, too, to aid in making the combustion more complete.

The exhaust steam is often used to preheat the water before it goes into the boiler. Such an arrangement is called a *feed water heater*. It is also possible to use an *economizer*, which uses the heat from the waste fuel gases to preheat the water. Both devices increase efficiency.

**340. How does the steam turbine work?** The wind blowing against the blades of a windmill drives the wheel. The water acting against the blades of a water turbine drives the turbine. Steam, too, can be directed upon the blades of a turbine to make it rotate rapidly. The different types of turbines differ mainly in the manner in which the steam is directed against the blades. In the Curtis turbine, Fig. 378, the steam is directed through nozzles in much the same manner as water is directed against the blades of the Pelton water wheel. From the first set of movable blades, the steam passes to a set of fixed blades, Fig. 379, so curved as to direct the steam against another set of movable blades. In this manner the steam passes from a set of movable blades to a set of fixed blades, and so on, until its expansive force is practically spent.

The Parsons and Westinghouse turbines consist of a cylindrical drum, or *rotor*, having a large number of blades set much like the blades of a windmill. (See Fig. 380.) The rotor is mounted in a *stator* (stationary) base or casing which has a large number of fixed blades, as shown in Fig. 381. The steam enters near one end of the turbine and flows along the space between the casing and the rotor, exerting its expansive force against the rotor blades and causing the rotor to spin rapidly. The diameters of both the rotor and casing are made larger near the outlet end to utilize more fully the expansive force of the steam.

**341. Steam turbine versus reciprocating steam engine.** On ocean liners, fast cruisers, and destroyers, the steam turbine is in common use. It has a decided advantage when high speed is desirable. For a given horsepower, the steam turbine occupies less space than a reciprocating engine. The rotary motion of the turbine causes much less vibration than the to-and-fro motion of the reciprocating engine. The steam turbine is more efficient when running at high speed. The rotor of the turbine

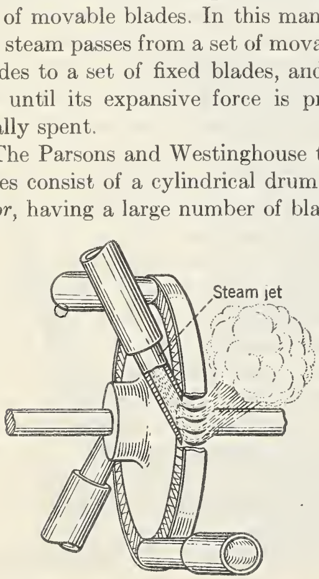


FIG. 378. The turbine principle.

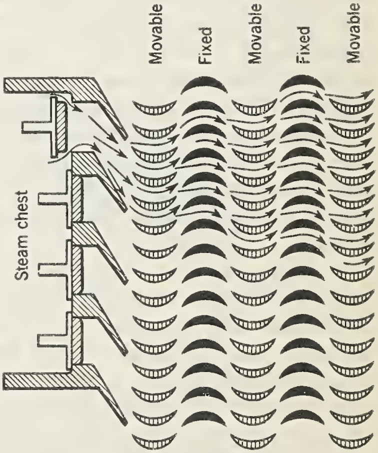
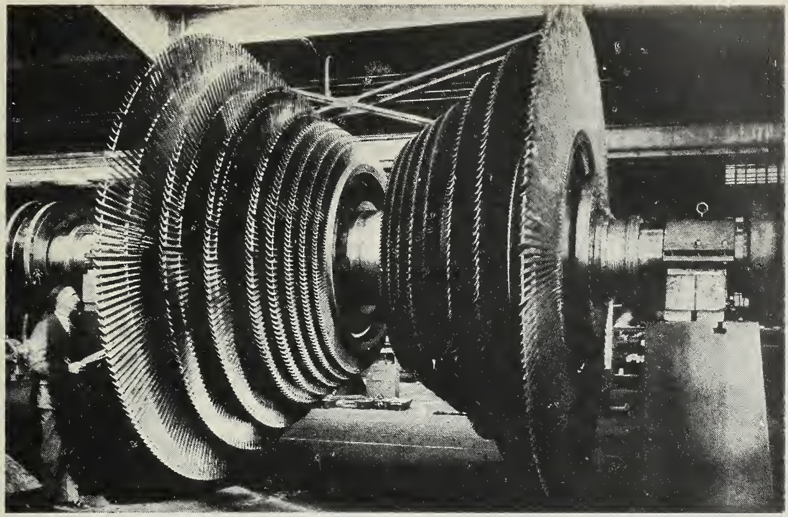
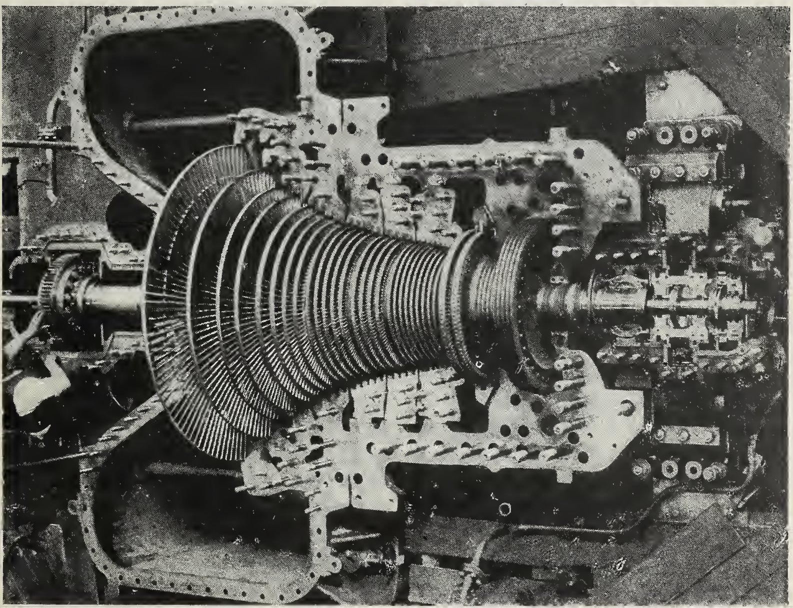


FIG. 379. Path of steam through a Curtis turbine.



Courtesy of Westinghouse

FIG. 380. Rotor of Westinghouse steam turbine. There are 1500 blades on this rotor. The longest blades are 38 inches in length, and move with a tip speed of 13 miles per minute, nearly as fast as a bullet.



Courtesy of Westinghouse

FIG. 381. Stator base and rotor of Westinghouse turbine. (20,000 kilowatt.) Tips of the longest blades move 1259 ft. per sec., faster than the velocity of sound.

may have the same shaft as the electric generator which it drives, thus making the transmission of power simple.

The steam turbine is not so efficient at low speed as the reciprocating engine, because the steam travels through the turbine at high velocity and much of its expansive force is lost when the speed is reduced. The reciprocating engine may be easily reversed, but the direction of the steam turbine cannot be reversed.

**342. How does the gas engine work?** The gas engine is an *internal combustion engine.* The carburetor vaporizes gasoline, benzol, or alcohol, and mixes the vapor with air to form the explosive mixture. Such an explosive mixture is ignited in the cylinder of the gas engine by means of an electric spark. The energy from successive explosions drives the piston and furnishes the power. The cylinder has thick walls, a piston which fits the cylinder so tightly that gas cannot pass, a connecting rod which connects the piston with the crankshaft, one valve to let in the explosive mixture, and another valve to let the waste gases escape. Let us see what happens in a single-cylinder *four-cycle,* or *four-stroke* engine during each cycle:

Cycle 1. To start the engine, we pull the piston down from a position near the top of the cylinder, either by means of a crank attached to the crankshaft or by means of an electric motor used as a self-starter. This produces a partial vacuum in the part of the cylinder above the piston. The explosive mixture from the carburetor is pushed into the cylinder through the valve $V'$, Fig. 382A. The outlet valve is closed. This cycle or stroke is called the *intake.* It fills the cylinder with the explosive mixture.

Cycle 2. As we continue to crank the car the piston moves upward. It takes more force now, because we are compressing the gas to about one fifth or one sixth of its former volume. During this *compression* cycle, or stroke, both valves must be closed, or we could not compress the gas. (See Fig. 382B.)

Cycle 3. When the piston reaches the top, or nearly so, an electric spark is produced between the terminals of a spark plug set in the metal cylinder head. The spark ignites the mixture and starts the explosion. The hot gases

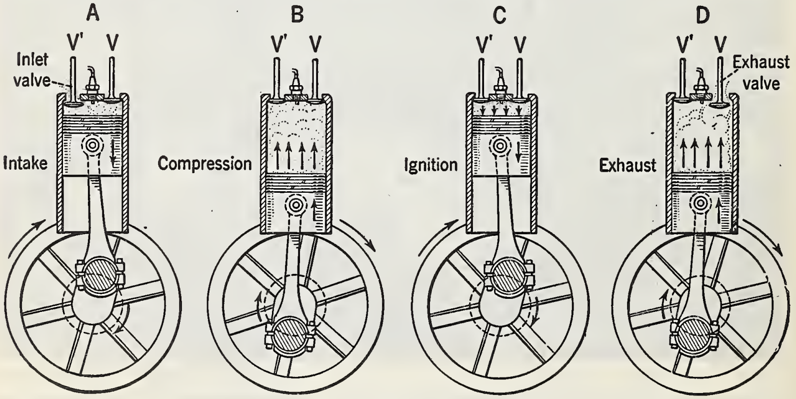


Fig. 382. The four-cycle gas engine. *A.* Intake. *B.* Compression. *C.* Ignition. *D.* Exhaust.

expand and drive the piston downward with great force. This is the *working* cycle or stroke of the piston. Both valves must be closed during this *ignition* cycle, or power stroke. (See Fig. 382C.)

CYCLE 4. The upper part of the cylinder is now filled with waste gases left after the explosion. On the next upstroke of the piston these gases are pushed out of the cylinder through the exhaust valve, $V$, Fig. 382D. The *exhaust* cycle, or stroke, completes the operation, and the whole process starts anew. There are generally 1200 or more complete cycles per minute.

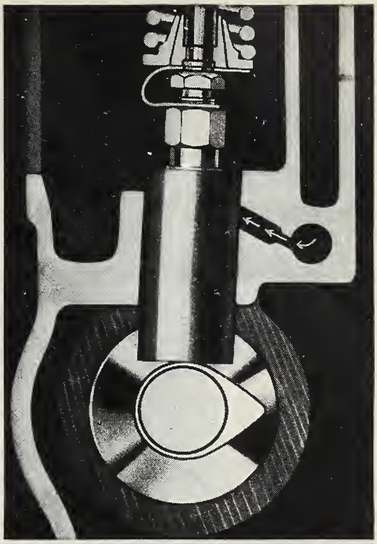
The Society of Automobile Engineers uses the following formula for finding the horsepower of a gas engine:

$$\text{H.P.} = \frac{D^2N}{2.5}.$$

In the formula, $D$ equals the diameter of cylinder in inches and $N$ the number of cylinders.

**343. What keeps the engine going between power strokes?** The single cylinder engine is working only one fourth of the time. To keep the parts moving between power strokes, a flywheel with a heavy rim is attached to the end of the crankshaft. The inertia of this wheel keeps the engine running fairly steadily.

*Multi-cylindered* engines are used for automobiles. When there is only one cylinder, there is one power stroke for every 720° of crankshaft revolution. With two cylinders, there is one power stroke for every 360° of revolution. With a four-cylinder engine, there is a power stroke for every half-revolution of the crankshaft, and the eight-cylinder engine furnishes a power stroke for every 90° that the crankshaft revolves. The more cylinders there are, the greater the flexibility of the engine. The flywheel may be made smaller, too. An eight-cylinder engine may be throttled down to run more slowly in traffic with less danger of stalling than a four-cylinder engine.



*Courtesy of the Studebaker Corporation*

FIG. 383. The projection on the cam lifts the valve stem as the shaft rotates.

**344. How are the valves controlled?** To control the valves, which must open and close at exactly the right time, cams are used. A camshaft is geared directly to the crankshaft, and turns with it. In Fig. 383, one can see how the cam lifts the valve stem as the camshaft rotates. A spring closes the valve just as soon as the cam projection has passed the end of the valve stem.

Fig. 384 shows a sectional view of one cylinder of a gas engine. The cams are shown, as well as the valve springs, and the manner in which the valves are seated. In actual practice, with an L-head motor, both valves are on the

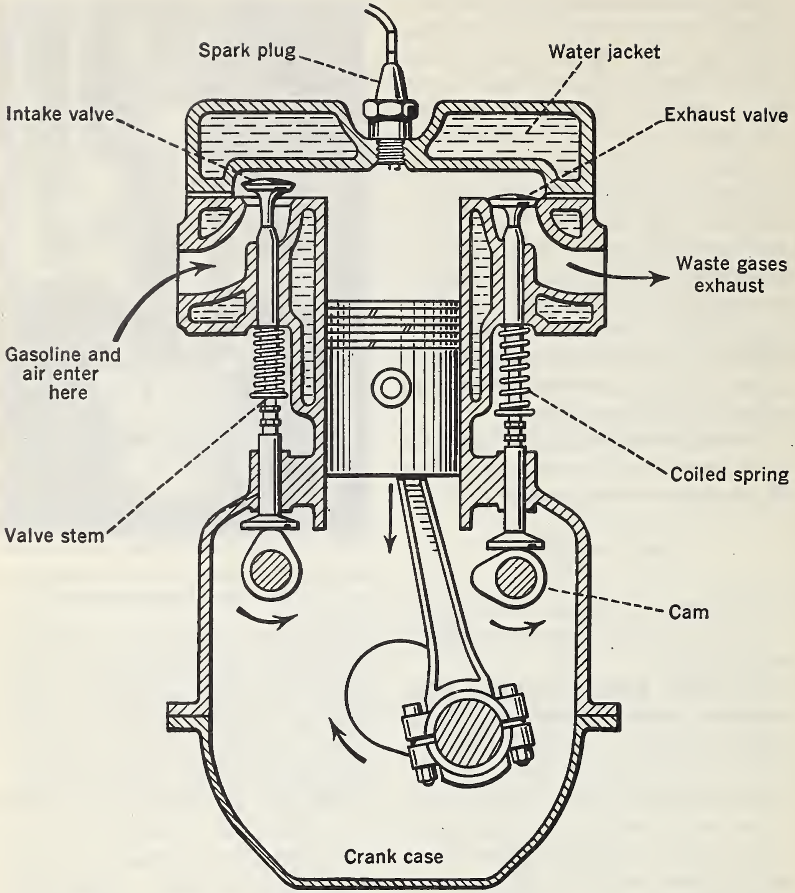
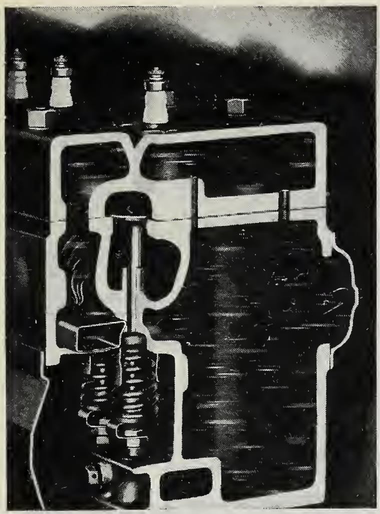

Spark plug
Water jacket
Intake valve
Exhaust valve
Waste gases exhaust
Gasoline and air enter here
Coiled spring
Valve stem
Cam
Crank case

Fig. 384. Sectional view of a gas engine.

same side of the engine cylinder, in line with each other so that they can both be operated from the same camshaft. In some engines, the valves are in the cylinder head. They are operated by a camshaft, through a rocker-arm mechanism.

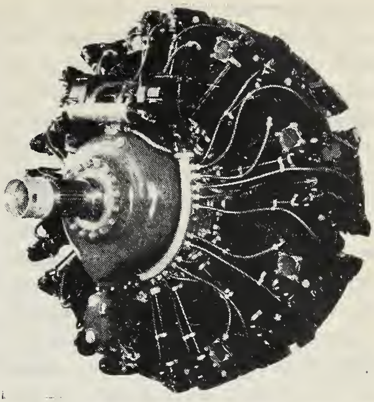
**345. How is the engine cooled?** The constant series of explosions in a gas engine soon heats the cylinder head, the piston, and the cylinder walls strongly. A gas engine does not work well until it is hot, but it must not get hot enough to "freeze" the piston or to warp or distort the walls or cylinder head unduly. Oil in the crankcase is splashed and pumped to all the moving parts to lubricate them and to help keep them cool.

In automobile engines the cylinder block is enclosed by a water jacket so that cold water can circulate around



Courtesy of the Studebaker Corporation

FIG. 385. Water circulates around the cylinders and the cylinder head to cool them.



Courtesy of Wright Aeronautical Corporation

FIG. 386. An 18-cylinder Wright Cyclone rated at 2000 horsepower.

each cylinder. (See Fig. 385.) A centrifugal pump is used to keep the water circulating. As the water becomes warm from the heat it absorbs, it flows out the top of the engine to the top of the radiator. In the tubes of the radiator it is cooled by air which is constantly drawn through the radiator. A fan behind the radiator causes the draft. The water which has been cooled in the radiator then returns to the lower part of the engine to absorb more heat.

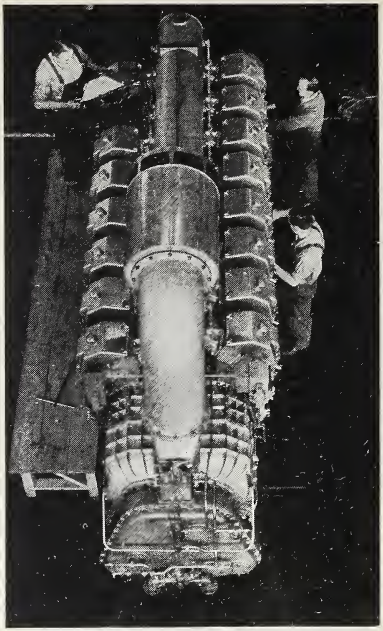
Motorcycle engines and airplane engines are generally air cooled. Flanges or fins attached to the outside cylinder walls absorb the heat and increase the surface exposed to the air so that the cooling will be more effective. (See Fig. 386.)

**346. What are the advantages and disadvantages of the gas engine?** 1. *Advantages*. The gas engine has an efficiency of about 25%, considerably higher than that of the steam engine. It is very compact and furnishes a high horsepower for its size. The Wright Cyclone engine, of the type used by Howard Hughes in his around-the-world flight, develops 1 H.P. for less than one pound of weight. The fuel, too, takes up very little room. Without the development of the gas engine, the airplane would not be practicable. The gas engine may be started at a moment's notice, and it can be stopped almost instantly. It does not waste fuel when it is stopped. The steam engine cannot be started until the fuel has been burning long enough to produce steam, and the fuel continues to burn after the engine is shut down. There is no need for stoking a gas engine, but the steam engine must be stoked frequently unless equipped with an automatic stoker. (See Fig. 376.)

2. *Disadvantages*. The gas engine is very sensitive. The spark must occur at the right time, and it must occur every time. The gas engine cannot be run economically at low speeds. It can-

not be reversed, except through the use of gear-reversing mechanism. The fuel is expensive and it promises to be even more so. The speed of a steam engine can be easily regulated by a throttle which governs the amount of steam entering the cylinders. While the speed of a gas engine can be varied by controlling the gas supply, yet gears are necessary to secure the proper variation in speed. The gas engine will not start under load, and a clutch mechanism is necessary to connect the engine with its load after the engine has been brought up to speed. The gas engine is rather noisy and the gases from the exhaust are disagreeable and poisonous to breathe.

**347. How does the Diesel engine work?** The four-cycle Diesel engine differs little in operation from the four-cycle gas engine. It is designed to operate on oils that are heavier and cheaper than gasoline. During the first cycle, pure air is drawn into the cylinder. On the upstroke, the piston compresses the air to more than 30 atmospheres. The heat of such great compression makes the air so hot that it will kindle the fuel and no electric spark is needed. Just before the beginning of the third cycle, the fuel valve opens to admit the oil vapors, which are forced into the cylinder by an air blast of high compression. The hot air ignites the fuel which burns during this power stroke of the engine. The waste gases escape during the exhaust stroke just as they do with a gas engine. The Diesel engine is compact and finds extensive use on submarines, some ocean vessels, and in power plants. (See Fig. 387.) Some of the streamlined trains that are now coming into extensive use are powered by Diesel engines. Considerable experimental work has been done in attempts to adapt the Diesel engine to use in automobiles. The promise of a motor which can use cheaper fuel is alluring, and a simplified ignition system is desirable.



*Courtesy of Westinghouse*

Fig. 387. The Diesel engine is compact. It utilizes inexpensive fuel.

**348. How does the semi-Diesel engine work?** In a *semi-Diesel* engine the compression is not so great. A firing pin is heated red hot and screwed into the end of the firing chamber in order to start the engine. Air is admitted during the first stroke and compressed during the second stroke of the piston. The fuel oil is forced into the cylinder just before the completion of the compression stroke. It vaporizes instantly as it strikes the hot walls, and it is kindled by the hot firing pin. Such engines find considerable use in small power plants.

## Summary

427 gm.-meters of work are equivalent to one calorie of heat. One B.T.U. is equivalent to 778 ft.-lb. of work.

Since heat may produce steam, and expanding steam produces pressure, the formation of steam furnishes one of the best methods of converting heat energy into work. The explosion of gasoline vapor is also much used for this purpose.

The ordinary steam engine uses from 7% to 20% of the total fuel energy. The gas engine is somewhat more efficient. The cam is used to change a reciprocating motion into a rotary one, and vice versa.

Grates may be equipped with automatic stokers to secure better combustion of fuels. To make a boiler more efficient, the water may be preheated by the use either of the exhaust steam or of the hot gases from the burning fuels.

Steam engines are of two types: (*a*) reciprocating; (*b*) turbine. In the steam turbine, the rotating part is driven by the force of the steam as it impinges upon the numerous blades of the rotor.

The four cycles of a gas engine are as follows: (*a*) Intake; (*b*) Compression; (*c*) Explosion; (*d*) Exhaust. The gas engine is more compact and more efficient than the steam engine.

The Diesel engine operates in much the same manner as the gas engine. No ignition system is necessary because the fuel-air mixture is so highly compressed that the heat of compression is great enough to kindle the fuel.

*How many of the following terms can you define or explain? (Two pupils can check each other to good advantage.)*

Joule
Steam engine
External combustion engine
Internal combustion engine
Condensing engine
Compound engine
Slide valves
Automatic stoker
Diesel engine
Gas engine
Semi-Diesel engine
Steam turbine

## QUESTIONS

1. Would you expect the steam leaving the cylinder of a steam engine to have the same temperature as the steam which enters the cylinder? Explain.

2. Why is ocean water unsatisfactory for use in steam boilers?

3. Why is the temperature of the steam in a pressure boiler more than 100° C.?

4. In steam boilers the flame from the fire-box is drawn through tubes surrounded by water. What is the advantage?

5. Explain why a gas engine does not start easily under a load.

6. What is the purpose of the baffle walls in the power plant of Fig. 376?

7. Why is the second cylinder of a double-expansion engine of larger diameter than the first?

8. Why does one need more food in winter than in summer?

9. Do you think that it takes more fuel to run a train from New York to Chicago in January than it does in July? Explain.

10. What is the meaning of the term "dead center" as applied to a steam engine?

11. What are some of the advantages of a Diesel engine over a steam engine? Over a gas engine?

12. Why is it necessary to have a cooling system for a gas engine?

## PROBLEMS

### Group A

1. A sled is drawn over the ice with a pull of 80 lb. How many B.T.U.'s will be produced if the sled is drawn 2 miles?

2. How many B.T.U.'s of heat energy does a 200-lb. man use in climbing a mountain 4000 ft. high?

3. If your body works at an efficiency of 28%, how many meters can you climb on the energy from a thick slice of bread (100,000 calories), if your weight is 60 kgm.?

4. Under a boiler 2000 lb. of coal are burned every hour. If each pound of coal yields 12,000 B.T.U.'s, what horsepower engine, working at an efficiency of only 15% can be operated by this boiler? How much energy is wasted?

### Group B

5. From what height must a block of ice fall to be melted by the heat of impact, assuming that 50% of the heat generated is absorbed by ice?

6. The average pressure of steam in a steam engine is 140 lb. per sq. in.; the diameter of the piston is 14 in., and the stroke is 24 in. How many ft.-lb. of work are done at each stroke? At each revolution of the flywheel? If the flywheel makes 400 revolutions per minute, what is the horsepower?

7. From a consideration of Problem 6, what factors affect the horsepower?

8. An eight-cylinder car has pistons which are 3.25 in. in diameter. What horsepower should the engine develop, S.A.E. rating?

9. Some modern engines give as high as 0.4 H.P. per cu. in. piston displacement. What would be the H.P. of the engine of Problem 8, if the length of the piston stroke is 4.5 in.? (Volume of piston displacement equals $(3.25)^2 \times 0.7854 \times 4.5 \times 8$.)

10. The horsepower as found by S.A.E. formula is approximately the one used for registration fees. (Problem 8.) The latter, as found by Problem 9, is the H.P. as given by salesmen to prospective buyers. What is the difference?

# Unit Seven

# *Sound*

## Preview

WHEN THE MOLECULES OF A BODY VIBRATE RAPIDLY, they set up heat waves. The vibrations of ordinary matter produce sound waves. If at least 16 sound waves reach the ear per second, they stimulate the auditory nerves, and we have the sensation of sound. When the number of single vibrations reaches some 38,000 to 40,000 per second, the sound waves produced by them do not affect any human ear. We have reached the limit of audibility. The ears of many persons are not sensitive to vibrations as low as 30,000 per second.

The term vibration has a different significance in some parts of Europe than it has in the United States. Here we use a complete vibration, which may, for example, correspond to an audio-frequency of from 10,000 to 20,000 complete vibrations, or from 20,000 to 40,000 single vibrations per second.

In our study of sound we shall learn that sounds vary in loudness, in pitch, and in quality. We shall find, too, that sound waves may be reflected to produce echoes, and they may be amplified more or less as we please.

Some sounds are extremely harsh and discordant, and the number of decibels to which one must listen is almost painful. Other sounds are pleasing and harmonious, and they may act as a sedative for overwrought nerves and weary muscles.

Later we shall learn that waves which are shorter than heat waves affect the optic nerves and cause the sensation of light. We detect the very short X-ray waves by their effect on photographic plates. Radio waves are detected by means of the audion tube or some other device used as a detector. Undoubtedly there are many waves present in the air or the ether about us that we cannot detect by means of any of our senses. For a long time, persons were unconscious of the radio waves which fill the ether or of the X rays that can be produced. One wonders sometimes just what he is missing because his senses are limited in the number of waves by which they are affected.

There is one interesting example. The so-called ultraviolet light has waves so short that the eye is not affected by them. *Ultrasonic* sound waves vibrate so rapidly that the ear is not affected by them. Many interesting experiments can be performed with them. Red blood cells are destroyed and small fish and frogs are killed by such *super*-sound waves which are vibrating millions of times per second. They hasten chemical action and cause water to boil at about room temperature. Ultrasonic waves, or supersonic waves as they are sometimes called, are used to increase the length of sailors' ears. Ordinary echoes are useful for short distances, but they spread out in all directions. Special supersonic waves travel in straight lines in one direction only, and rebound in the same straight line. A special submarine detector uses such a beam, which bounds straight back to the sending ship, where it is picked up by special detectors of supersonic signals, which are inaudible to the ear itself. Ships in a fog, or submarines, even when lying at rest, can be located by such supersonic signals.

# Sound

## 1. Sound and Wave Motion

**349. What is the source of sound?** Let us clamp firmly in a vise one end of a thin strip of wood or steel. When the other end is struck a sharp blow, or if it is bowed or plucked, the free end of the strip will vibrate to and fro. (See Fig. 388.) If it vibrates rapidly enough, it will produce a humming sound. If we pluck, strike, or bow a violin string, we throw the string into vibration and sound is produced. From such experiments it can be shown that *sound waves have their origin in vibrating matter.*

Let us hold a tuning fork and strike one of the prongs a sharp blow. We can hear the sound which the fork produces. We can prove that the prongs are really vibrating rapidly by holding them in a glass of water as shown in Fig. 389. The water will spatter as the prongs of the fork vibrate back and forth, although the vibrations are so rapid that the eye cannot detect them. Any matter, even air itself, may vibrate rapidly enough to produce *sound waves.*

**350. How do sound waves get to our ear?** In a telephone system, we need a transmitter, some wires to transmit electrical waves, and a receiver. Similarly, if we are to hear, we must have a vibrating body, corresponding to the transmitter, which produces the sound waves. Our ear corresponds to the telephone receiver as it picks up the sound waves. Since there are no wires to transmit the sound waves from the voice of a speaker to the ears of a listener, we

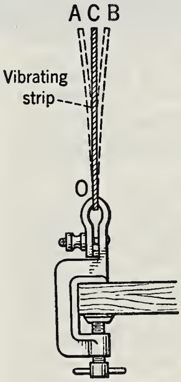


Fig. 388. A vibrating body produces sound waves.

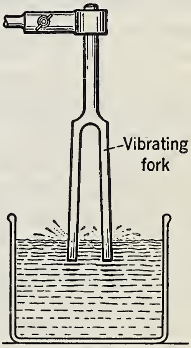


Fig. 389. The vibrations of the fork disturb the water.

### Vocabulary

Microphone, a sensitive telephone transmitter.

Acoustic, pertaining to the science of sound or of hearing.

Resonance, the reinforcement of one sound wave by another.

Interference, the extinction or reduction of one sound wave by another.

Refraction, the bending of a sound wave out of its path as it enters a denser or rarer medium.

Decibel, a small unit for measuring loudness.

may well inquire how sound waves travel.

In the majority of cases, the sound waves travel through the *air* from their place of origin to our ears. Nearly all the sounds we hear come to us through the air as a transmitting medium. As one climbs a mountain, he must speak a little louder in order to be heard. The air on the mountain is less dense than the air in the valley and it does not transmit the sound waves so readily. Dense gases are better transmitters of sound waves than rare gases.

If we put a small alarm clock or an electric bell under a bell-glass and let it continue to emit sound waves as we pump the air out of the bell-glass, we find that the sound becomes fainter and fainter as the air grows thinner and thinner. If we can get a fairly good vacuum, the sound becomes almost inaudible. The sound increases again as we permit air to enter. Thus we are led to conclude that sound waves do not travel through a vacuum, but that they travel readily through air. (See Fig. 390.)

If we hold our ears under water, we can hear the paddle wheels of a steamer for rather a long distance. The sound waves come to us through the water itself. During World War I, vessels were fitted with listening devices, or "ears," which were attached below the surface of the water. They were used to detect the presence of hostile submarines. Fishermen believe that fish have very sensitive ears. They doubtless hear clearly those sounds which have their origin in the water itself, but it is doubtful whether they hear sounds whose waves have their origin in the air, ordinary conversation for example. *Liquids are better transmitters of sound waves than air or other gases.*

If someone in the basement taps on a steampipe, the sound can be heard distinctly in the rooms above. This shows that the metal pipe transmits sound waves. Michael Pupin tells us that as a shepherd boy he was accustomed to lie down with his ear close to the ground to hear sounds more clearly as they traveled through the solid earth. A streetcar can be heard at a considerable distance by a person who stands near a trolley pole, because the sound travels readily through the solid trolley wire and is transmitted to the pole. A famous inventor, who was hard of hearing, used to listen to phonograph records by resting his head against the instrument so that the vibrations could travel through the bones of the head. Some persons who are partially deaf can tune or play a violin well, because the chin rests on the instrument and the vibrations are transmitted through the jawbone. In general, *solids are better transmitters of sound than either liquids or gases.*

**351. The ear is a receiver of sound waves.** If we study Fig. 391, we see that the ear is well adapted to receive

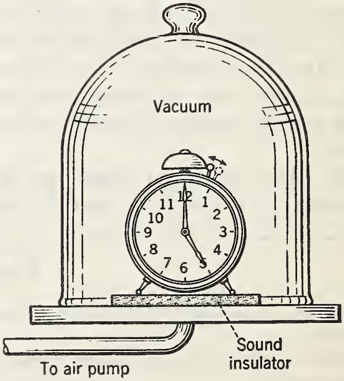
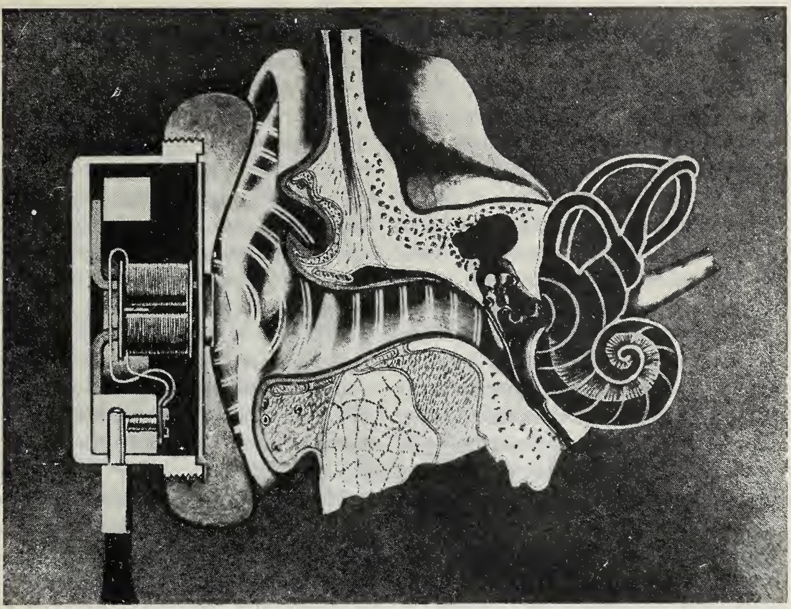


Fig. 390. The vacuum is not a transmitter of sound.



*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 391. The sound waves from the receiver are transmitted to the inner ear. Note the condensations shown in external ear.

sound waves. The outer ear is so shaped that it collects sound waves and conducts them to the drum of the middle ear. Just as in olden days all roads were said to lead to Rome, so all the channels of the outer ear lead inward toward the middle ear. The vibrations which reach the ear drum are amplified by the small bones of the middle ear, which act as levers to multiply the impulse. In the inner ear the vibrations are led to the auditory nerves which are spread out along the snail-shaped portion of the inner ear. When the vibrations stimulate the auditory nerves, they carry to the brain sensations which we call *sound.*

If a tree falls in a forest where there are no ears to hear it, is sound produced? To answer this question, which is a very old one, it is necessary to define sound. In the *physiological* sense of the term, three things are necessary for the production of sound: (*a*) a vibrating body; (*b*) a medium for transmitting sound waves; (*c*) an ear, which serves as a receiver. In the *physical* sense of the term, the word *sound* is synonymous with *sound wave.* The answer depends upon the definition used.

**352. How can one insulate against sound?** We sprinkle sawdust on the floor to deaden sound. We wear shoes with rubber soles and walk more quietly than we do with leather soles. Rugs help to prevent noise, and some floors are covered with corkboard. In some modern apartment houses, material which is porous or has a low elastic constant may be used in the walls to deaden sound. Studios used for radio broadcasting are soundproofed to shut out disturbing sounds. Celotex finds extensive use for sound insulation. Asbestos mats and silence cloths are used on dining-room tables to prevent the clatter of dishes. Cork floors are used in some churches.

**353. How fast does sound travel?** We sometimes see a lightning flash and then hear the thunder several seconds later. If a pistol is fired at a distance of several hundred feet, we can see the flash a brief interval before we hear the report. For short distances light is practically instantaneous; hence the time interval between the flash of the pistol and the report must be equal to the time required for sound to travel the intervening distance.

The velocity of sound was measured by setting up two cannon on hills several miles apart and firing them alternately. The distance between the two cannon was carefully measured, and also the time required for the sound to travel that distance. By firing from different positions, the errors due to the velocity of the wind were eliminated. Indirect methods for measuring the velocity of sound have also been used. The average of a large number of trials is rather more than 1087 feet per second. We are not far wrong if we use a number which is easier to remember and say that *the velocity of sound in air at 0° C. is 1090 ft. per second.* As the temperature rises, the velocity increases. *An increase in temperature of 1° C. causes an increase in velocity of about 2 ft. per second.* At 15° C., for example, the velocity is 1120 feet per second. In the metric system, the velocity at 0° C. is about 332 meters per second, and the increase in velocity is about 0.6 meter per degree Centigrade.

**354. How fast does sound travel in other media?** In 1827 two Swiss scientists measured the velocity of sound in water. At one station a bell was rung under water at the same instant that some powder was exploded at the surface. An observer some 8 miles distant measured the interval of time between the flash of the powder and the sound heard through an ear trumpet under water. They found the velocity of sound in water to be 1435 meters per second, or about four times the velocity of sound in air. In some solids, the velocity is even greater. In steel, for example, it is more than 15 times as great as in air. (See Table 8, Appendix B.)

**355. What is meant by sound ranging?** This science, which was developed during World War I, made use of a knowledge of the velocity of sound to locate enemy field guns from the reports of their firing even when the flash was completely concealed. Listeners at various microphones scattered over a given area behind the trenches recorded with great precision the exact time when the report of a gun was received.

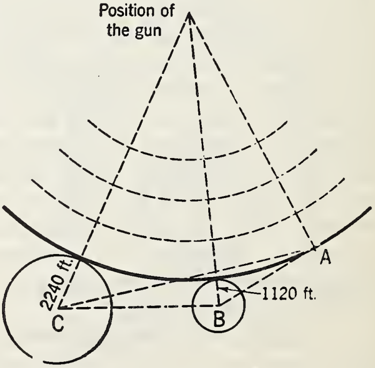


Fig. 392. Sound waves spread out along the radii of concentric spheres.

Suppose we let the points $A$, $B$, and $C$ of Fig. 392 represent the positions of three listeners. The distances between their stations had all been accurately measured. $B$ hears the report of the gun just 1 second after $A$ hears the same report, and $C$ hears the report 2 seconds later than $A$. Just as water waves spread out in all directions from a pebble thrown into a pond, so the sound waves from the gun as a center spread out along the ground in ever-increasing circles. If the velocity of sound on that day was 1120 ft. per second, then we draw from $B$ and $C$ as centers two circles having radii whose relative lengths are 1120 (representing 1 second of time) and 2240 (representing 2 seconds of time) respectively.

An arc is then drawn through the point $A$ and tangent to both circles. This arc forms a part of a circle, the circumference of which represents the advancing sound wave. The center of that circle is the point from which the gun was fired. Since the sides of the triangle $ABC$ are known and the included angles can be measured, it is possible to calculate by trigonometry the position of the gun. The method was so accurate that a gun several miles distant could be located within a few feet and then destroyed by gunfire.

**356. What is meant by vibration?** In a preceding section we learned that a thin strip of steel may be used to illustrate vibrations. When one end is clamped firmly, and the other end is struck a sharp blow with a hammer, the free end vibrates, or moves to and fro, as shown in Fig. 388. Just as in the vibration of the pendulum, the movement from $A$ to $B$ constitutes a *single vibration,* and the movement from $A$ to $B$ and return a *complete vibration.* The *amplitude* of the vibration is measured by the distance $AC$; the *period* is the time required for one complete vibration; and the *frequency* is the number of complete vibrations per second.

**357. There are two kinds of vibration.** 1. *Transverse.* Let us fasten the ends of a stretched spiral spring several feet long and then pluck the spring at *right* angles to its length. (See Fig. 393$A$.) A wave is set up which travels along the spring from one end to the other and then returns by reflection. A wave that moves at right angles to the path along which it travels is a *transverse wave.*

Water waves, with which we are all familiar, are transverse waves. As the wave advances, the water rises and falls, but there is actually little or no forward movement of the water itself, except possibly near the shore. The fact that there is no progressive motion of matter in transverse waves is clearly shown by a field of waving grain. Before the wind, the stalks of grain bend forward and downward; after the wind has passed, they bend upward and backward. The wave may travel entirely across the field, but of course there is no progressive movement of the stalks of grain themselves.

2. *Longitudinal.* Suppose we compress several turns of the stretched spiral spring of Fig. 393$B$ and then re-

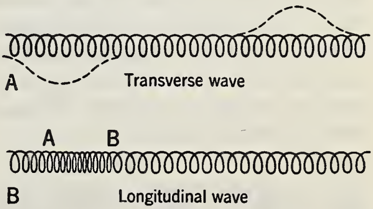


Fig. 393. Diagram $A$ shows transverse waves. Diagram $B$ shows longitudinal waves.

lease them quickly. A wave is produced that vibrates in the same direction as the path along which the wave travels. Such a vibration is *longitudinal.*

**358. Sound waves are longitudinal.** Look at Fig. 388. While the steel strip there shown is moving from $A$ to $B$, the air immediately in front of it is compressed or condensed, while the air immediately behind it expands and becomes rarefied. As the strip moves back again from $B$ to $A$ the air that was compressed by the first movement now expands and the air that was expanded is compressed. As the strip continues to vibrate, a series of *condensations* and *rarefactions* is produced. In Fig. 394 the crowded lines represent the condensations and the others the rarefactions. Such a *train of waves* is *longitudinal;* it develops in the direction of the path along which the waves are traveling.

There is little forward movement of air in such a wave train, since each pulse communicates its energy to the air in front, in much the same way as the collision balls of Fig. 395 communicate impulses. If ball $A$ is raised and then let fall, the impulse is communicated to each ball in turn, until $C$ is reached. This ball flies out to the position shown in the figure, but the others remain stationary. We may place six boys in line, and let each one place his hands on the shoulders of the boy immediately in front of him. The boy at the rear of the line gives a sudden push. That impulse is communicated from one boy to another until the boy at the head of the line is reached. He alone will be pushed forward.

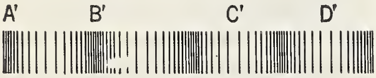


Fig. 394. A train of waves.

**359. How are sound waves measured?** If the wave is transverse, we measure its length by finding the distance between a particle in one wave and a corresponding particle in the same phase of the next wave. (See Fig. 396.) The highest parts of the waves as shown at $C$ and $D$ are called *crests;* the point $T$ shows the trough of the wave. The length may be measured from crest to crest by finding the distance between $C$ and $D$, or by measuring the distance from $A$ to $B$, or from $x$ to $y$.

If a wave is longitudinal, we find its length by measuring the distance between successive condensations, or between successive rarefactions. (See Fig. 394.) The length of the wave is measured from $A'$ to $B'$ or from $C'$ to $D'$.

**360. How are velocity, wave length, and vibration rate related?** Suppose that we have a tuning fork which is vibrating at a frequency of 275 times per second on a day when the velocity of sound is 1100 ft. per second. It is evident that we will have 275 condensations with an equal number of rarefactions forming a train of waves 1100 ft. in length. We can find the length of each wave by dividing the velocity, 1100 ft., by the total number,

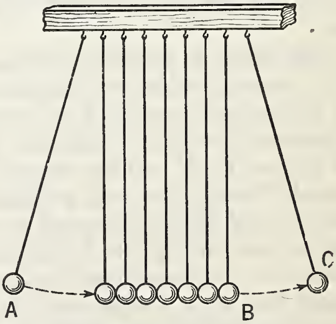


Fig. 395. How waves progress.

275. (1100 ÷ 275 = 4.) Hence each wave is 4 ft. long. The first wave will travel 4 ft. before the second one starts, and the first one will be 8 ft. distant before the third one has started.

Physicists use the letter $v$ to represent the velocity, the letter $n$ to represent the frequency or the number of vibrations per second, and the letter $l$ to represent the wave length. Then the mathematical relationship may be expressed by the formula,

$$v = nl.$$

If any two of the quantities are known, the third one may be calculated by use of the formula.

PROBLEM. A fork having a frequency of 320 has a wave length of 3.5 ft. Find the velocity of the sound in air. What was the temperature?

*Solution.* From the formula, $v = nl$, we see that the velocity is equal to the product of the frequency and the wave length. 320 × 3.5 ft. = 1120 ft., the velocity in feet per second. To find the temperature, we subtract 1090 ft., the velocity at 0° C. from 1120 ft. The difference equals 30 ft. 30 ÷ 2 = 15, the number of degrees needed to cause an increase of 30 ft. per second in the velocity. Hence the temperature was 15° C. We shall have occasion later to use the formula, $v = nl$, in calculating radio wave lengths and frequencies.

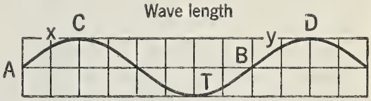


FIG. 396. Transverse waves.

## 2. Reflection of Sound

**361. How are echoes produced?** Everyone has stood at some distance from a cliff or forest and listened to the echo which is produced as he calls loudly. Just as a rubber ball rebounds from a hard surface, so sound waves are reflected when they strike against a medium of greater density. If the sound wave travels back along the perpendicular to the reflecting medium, a person in its path hears the sound repeated. *An echo is a repetition of a sound due to the reflection of the sound wave from some surface.* A person standing between parallel walls may hear a sound repeated several times as the sound wave is reflected back and forth between the walls. A remarkable case of this kind occurred in a city in Indiana. The word "Knickerbocker," when uttered at one particular spot, was re-echoed twenty times before it became inaudible. The rolling of the thunder is caused by echoing and re-echoing as the sound wave is reflected from cloud to cloud, or from a cloud to the earth.

The reflected sound wave travels at the same velocity as the direct wave. On a day when the temperature is 20° C., the velocity of sound is 1130 ft. per second. A cliff 1130 ft. distant will produce an echo after 2 seconds. It will take one second for the direct wave to reach the cliff, and one second for the reflected wave to return.

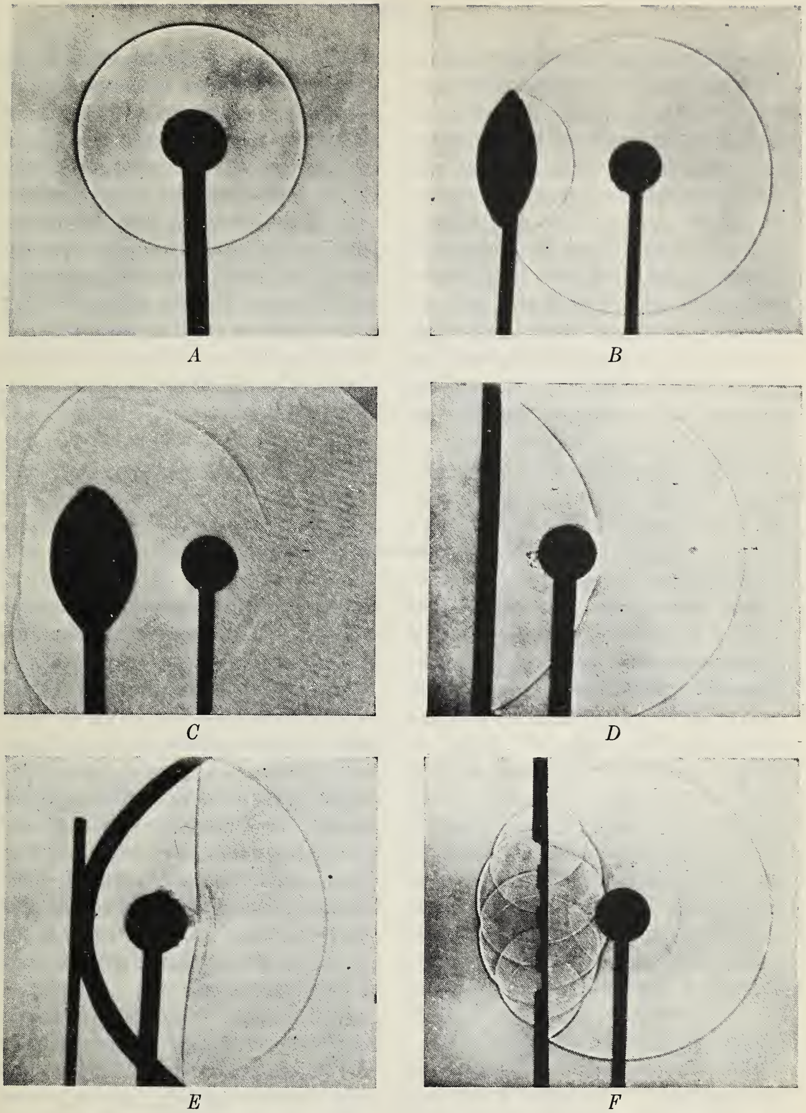
**362. How may echoes be useful?** In foggy weather the captain of an ocean vessel may use echoes to determine his nearness to a rocky coast or an iceberg. If the blast of the whistle is returned quickly, he knows that he is approaching danger. This method of sensing danger is not altogether dependable because weather conditions may make it hard to hear the echoes or judge the direction. Many vessels are also fitted to receive submarine signals, since an underwater signal is not affected by weather conditions. Iron tanks are fitted near the bow of the vessel, one on either side of the ship. Each tank, which is filled with salt water, contains a microphone, which is connected with telephone receivers in the pilot house. A sound signal is produced, which is transmitted through the water to some distant object. Then it is reflected back to the ship, where it is transmitted through the side of the ship to the microphone, which amplifies the sound in the receiver. Just as a person with two ears can determine the direction from which a sound comes, so the two receivers enable a listener to judge from what direction the signal is coming. The time elapsed enables him to calculate the distance.

The *depth of the water* may be determined in a similar manner. A sound produced from the hull of the vessel travels downward through the water and is reflected back from the bottom of the ocean. By measuring the time which elapses between the sending and the receiving of such a signal, the depth of the ocean can be calculated, since we know the velocity of sound in water. This method of finding the depth of water is rapidly replacing the line and lead formerly used for sounding.

**363. The acoustic properties of buildings are important to speakers.** In some large halls and assembly rooms, echoes prove troublesome. The duration of sound is about $\frac{1}{10}$ of a second. That means that the sensation of sound continues for $\frac{1}{10}$ of a second after the sound stops. If a sound wave is reflected from one wall of a room before the original sound dies out, confusion will result. To illustrate, suppose that sound has a velocity of 1100 ft. per second. In $\frac{1}{10}$ of a second the sound will travel 110 ft. If an assembly hall is just 55 ft. long, a sound uttered at one end will travel the length of the hall and back again in $\frac{1}{10}$ of a second. Such halls are difficult for speakers because the echoes are so troublesome. A trained speaker will so time his words and syllables that the echo does not produce confusion. Quite often the echoes disappear when the hall is filled with people, since the sound waves are broken up. Furniture and draperies are also helpful in breaking up sound waves and preventing troublesome echoes.

**364. What are whispering galleries?** Some large buildings have remarkable acoustic properties. Sometimes a dome-shaped ceiling will so reflect the sound waves that they are focused at one particular place. In the Capitol building at Washington, whispers that are uttered near one side of the Hall of Statuary can be heard distinctly near the opposite side, although they are inaudible in the center of the room, only half as far away. A low whisper uttered near one side of St. Paul's Cathedral in London is distinctly audible at the other side, over 100 ft. away. A pin dropped on a railing near one end of the Mormon Tabernacle in Salt Lake City can be heard clearly at the other end, over 200 ft. distant.

**★365. Sound waves can be photographed.** The series of photographs shown in Fig. 397 were taken by Professor A. L. Foley, of Indiana University. They show very clearly just how the actual sound waves behave.


A B C D E F

*Courtesy of Professor A. L. Foley*

Fig. 397. Photographs of sound waves taken by Professor A. L. Foley of Indiana University. *A*. Spherical sound wave taken 0.0001 sec. after the spark that produced the wave. *B*. Sound wave taken 0.00015 sec. after the spark. Shows expanding wave and reflection from convex surface of a gas lens. *C*. Same wave 0.00023 sec. after the spark. Shows original wave, reflected portion, and plane wave transmitted through gas lens. *D*. Spherical wave reflected from plane mirror. *E*. Sound wave reflected from parabolic mirror. Reflected wave is plane. *F*. Reflector is sheet of tin with four rectangular openings. Waves are reflected from five sections of tin which have become new centers of disturbance. The waves passing through the openings are diffracted.

The origin of the sound wave was a spark produced between electric terminals. This wave spread out in all directions, forming larger and larger spheres as it advanced, in much the same way that a toy balloon increases in size as we inflate it. When the sound wave strikes a plane surface through which it cannot pass, the part of the wave farthest in advance strikes the reflector first and is turned back. The other portions are then reflected in turn, as shown at *D*. The reflected wave would represent the echo of the original sound. From a curved surface the sound wave is also reflected, but its curvature is increased as it is turned back from a convex surface, as in *B;* its curvature is decreased when it is turned back from a concave surface, as in *E*. Sound waves are refracted, or bent out of their course, in passing through a lens filled with some gas either denser or rarer than air. In *C* of the figure we see that both reflection and refraction occur, part of the wave passing through the lens and a part being reflected.

## 3. Loudness and Pitch

**366. How do sounds differ?** The crash of thunder may be very loud; a whisper may be soft and low. The chirp of a cricket has a note of shrill, high pitch; the growl of a bulldog is a deep bass. The voice of Caruso or Jenny Lind was of pleasing quality; some other voices are not so pleasing, and we would not pay very much to hear some persons sing. These three examples show how sounds differ from one another. Each one is distinct from the others, and the characteristics do not overlap. Sounds differ from one another in three fundamental properties: (*a*) *loudness,* or *intensity;* (*b*) *pitch;* (*c*) *quality.*

**367. What do we mean by intensity and loudness?** 1. *Intensity.* If we *throw* a small pebble into the water, higher waves are produced than by dropping it into the water more gently. When a bow is drawn across a violin string lightly, only a small amount of energy is imparted to the string, and the sound wave is not very *intense.* More vigorous bowing increases the *amplitude* and the sound becomes more intense.

A large stone thrown into a pond causes a larger volume of water waves than a small pebble. A large tuning fork produces a greater volume of sound waves than a small one. Hence the large fork produces a more intense sound. A cannon produces a more intense sound than a toy pistol. From these observations, we conclude that the *intensity of sound is increased by increasing the amplitude and the area of the vibrating body.*

2. *Loudness.* Sometimes *intense* sounds do not appear very *loud* to us. The medium through which they come may transmit sounds poorly, or we may be too far distant to hear them distinctly. We have already compared the different media through which sound waves are transmitted. Since sound waves are given off in all directions from a vibrating body, the waves spread out over a greater area as they

advance. The areas of the surfaces of these concentric waves are proportional to the squares of their distances from the center. A bell will appear only one-fourth as loud to a person one-half mile away as it does to one who is only one-fourth mile distant. We conclude that the *loudness of a sound is inversely proportional to the square of the distance from the source, and that it depends upon the medium through which the sound is traveling.*

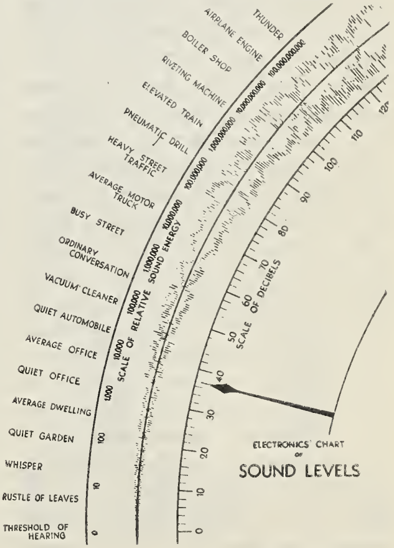
**368. Special conditions affect loudness.** As we have seen, sound waves ordinarily spread out in all directions from the vibrating body. But if one uses a *megaphone*, the sound wave to a large extent is directed by the sides of the megaphone and is intensified in one direction. In such cases, doubling the distance does not decrease the loudness to one fourth for those persons directly in front of the megaphone. The same principle is used in the *phonograph horn* or the *automobile horn*. The *speaking tube*, which is used extensively in apartment houses, is similar to the megaphone in general principle. In some assembly halls, *sound reflectors* are used over the stage or platform to secure a better distribution of the sound waves to the different parts of the room. For large assembly halls, amplifying horns are extensively used.

In the *ear trumpet*, the principle of the megaphone is reversed. The larger end receives more of the sound wave and thus augments the sound by conducting a larger volume of the sound wave to the ear. The mouthpiece of a telephone transmitter is similar in its application.

In the *stethoscope* as used by physicians, a diaphragm much larger than the drum of the middle ear is used to increase loudness. Such a diaphragm collects more sound waves than the drum could possibly receive and transmits them by means of rubber tubes to the ears of the listener. The stethoscope was used in the dugouts during the war to listen for tunneling work preparatory to the placement of mines by the enemy.

**369. How is loudness measured?** The *bel*, named for Alexander Graham Bell, is the unit used for measuring the loudness of a sound. A smaller unit, the *decibel* (one tenth of a *bel*) is often used instead of the *bel*. Sounds may be barely audible, or they may be so loud as to be almost painful. Between these extremes are the ordinary sounds heard in the home, the school, the streets, and the factories. Instruments are in use to compare the loudness of various sounds and rate them in decibels. (See Fig. 398.)

For example, a whisper ranges from



Courtesy of Electronics

Fig. 398. Loudness of sound is measured by decibels.

10 to 20 decibels; a rather quiet office, from 20 to 40 decibels; a modern automobile, 10 to 50 decibels; ordinary conversation, about 60 decibels; motor trucks and heavy street traffic, 70 to 80 decibels; elevated trains, pneumatic drills, and riveters, 90 to 100 decibels; thunder, about 110 decibels; sounds ranging from 120 to 130 decibels are almost painful. Men become numb, shocked, and in some cases deafened by artillery fire.

**370. Upon what does pitch depend?** A piccolo has a shriller pitch than a flute. It may be louder or softer. A woman's voice has a higher pitch than that of a man. It may be softer or louder, and it may have either better or poorer quality. Pitch is entirely independent of both loudness and quality. Let us use a siren disc to show upon what factors pitch depends.

The disc of Fig. 399 has four rows of regularly spaced holes, numbering 24, 30, 36, and 48 respectively. It is mounted so that it can be rotated rapidly. Suppose we direct a stream of air against the inner row of holes, 24 in number, while it is rotating rapidly. Such a stream of air is thrown into vibration, and of course the number of vibrations per second is equal to the number of holes times the number of revolutions per second. If the speed is increased the pitch rises. If we keep the speed constant and direct the stream of air against the outer row of holes, 48 in number, a note an octave higher is produced. If a stream of air is directed against each of the four holes successively, beginning with the inner row, the notes *do, mi, sol, do′* are produced. From this experiment, we conclude that the *pitch of a note or tone depends upon the number of vibrations or pulses which the ear receives per second.* The string of a piano must vibrate twice as fast to produce the note C′ as a string does which is producing the note C, an octave lower.

Since $v = nl$, then the wave length of a fork vibrating 512 times per second will be only half as long as that produced by a fork vibrating 256 times per second. *The pitch of the former fork is higher than that of the latter because twice as many wave lengths reach the ear per second.* The pitch rises as the frequency increases and it falls as the wave length increases.

**★371. What is Doppler's principle?** When the distance between the ear and a vibrating body does not change, the number of pulses reaching the ear per second is exactly equal to the frequency of vibration. If we are moving toward the vibrating body or if it is approaching us, we will then receive more pulses per second than the vibrating body is producing. For this reason, the whistle of a rapidly *approaching* train *rises* in pitch. As the train *recedes*, the pitch *falls*.

Suppose that the velocity of sound is 1140 ft. per second and that the whistle has a frequency of 300 vibrations per second. If the train is approaching at a velocity of 45 miles per hour,

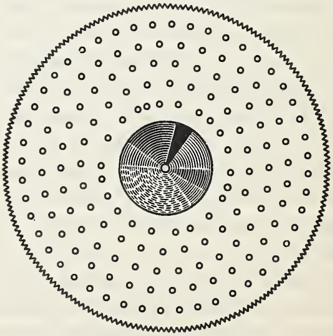


Fig. 399. The siren disc.

or 66 ft. per second, the length of the sound wave will have been reduced from 3.8 ft. to only 3.58 ft. ((1140 − 66) ÷ 300). The pitch will now correspond to 318.4 vibrations per second. Hence the listener receives 18.4 more pulses per second than the whistle produces. As the train recedes, the new wave length is increased from 3.8 ft. to 4.02 ft., and the pitch falls to only 283.5 vibrations per second. (1140 + 66) ÷ 300 = 4.02 ft. Such a rise in pitch when a sounding body approaches, or fall in pitch when it recedes, is known as *Doppler's principle.* The auto horn may be an example.

## 4. Resonance and Interference

**372. What are forced vibrations?** A tuning fork vibrating freely has a natural vibration rate which depends upon its length, thickness, and the material of which it is made. The strings of a musical instrument also have natural vibration rates free from external influences except gravity and friction. It is possible, however, for one vibrating object to impress its vibration rate upon another that has a different natural frequency. When we hold the stem of a vibrating tuning fork against a table, the tuning fork impresses its vibration rate upon the table. Energy is transmitted through the stem of the fork, and the table is *forced to vibrate* in response to the periodic force thus applied. A thin string stretched from one post to another does not produce a very intense sound when it vibrates. When the same string is stretched across the bridge of a violin, the thin wood of which the violin is composed is forced to vibrate in response to the vibrations of the string. The intensity of the sound is increased by the *forced vibrations* of the instrument. The sounding board of a piano is another example of forced vibrations used to intensify sound.

**373. What are sympathetic vibrations?** Suppose that we have given two mounted tuning forks, Fig. 400, both having the same vibration rate. We may let a pupil near the rear of the room hold one fork near his ear while someone at the front of the room strikes the other fork a sharp blow to throw it into vibration. After a few moments, the prongs of the latter fork may be touched to stop its vibrating. The pupil at the rear of the room will discover that the fork which he holds is now vibrating feebly. The impacts of the sound waves from the first fork fell upon the second fork in regular succession and caused it to vibrate sympathetically. The strings of a violin may be heard vibrating softly when a person playing a piano in the same room strikes notes which have the same pitch as that which the strings could produce. *Sympathetic vibrations* occur when the natural vibration rates

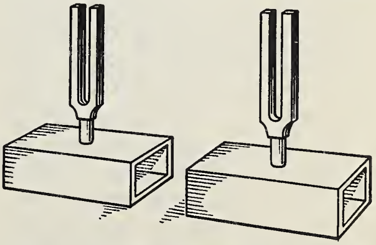


Fig. 400. Tuning forks used to show resonance.

of two objects are the same, or when the vibration rate of one of them is a multiple of the other. If we change the natural vibration rate of one fork by adding a weight to one of its prongs and then repeat the experiment, no sympathetic vibrations are produced. Both forks must have the same frequency. The principle of tuning a radio set is not essentially different from sympathetic vibrations.

**374. What is resonance?** Let us hold a vibrating tuning fork over a cylindrical tube partly filled with water. Now, if we pour water into the tube gradually, it is possible to find a point where the sound wave which is reflected back from the water surface unites with the direct wave from the fork and reinforces the sound. Thus a condensation of the reflected wave unites with the condensation of the direct wave to amplify the sound, just as the piling of the crest of one water wave upon the crest of another wave makes the resulting wave higher. A tube so adjusted that it will reinforce sound waves is called a *resonator*.

Look at Fig. 401. If we are to have resonance, the sound wave must travel down the tube and back while the prong *c* of the fork is making a single vibration from *a* to *b*. Under such conditions the condensation will be reflected back in time to meet the next condensation as it is starting down the tube. While the prong of the fork is making one complete vibration, the sound wave travels up and down the tube twice, or *four times the length of the tube*. We may define *resonance as the reinforcement of sound by the union of the direct and reflected sound waves.* From the experiment just studied, *we find that a closed tube produces the best possible resonance when its length is one-fourth that of the sound wave which it reinforces.* Whence,

Wave length ($l$) equals 4 (length of closed tube, $l'$).

When a vibrating fork is held over an *open* tube, resonance is also produced. Experiment shows, however, that such a tube produces the *best resonance when its length is just one-half the wave length of the sound it reinforces.* With an open tube, the condensation spreads out when it reaches the end of the tube, and a condensation is returned as a rarefaction.

**375. How can one sound wave interfere with another?** If the crest of one water wave meets the crest of another water wave, it piles up the water to make an even higher wave. So it is possible to have the crest of one water wave fall into the trough of another wave and make the water surface level. In a similar manner, since the meeting of the condensation of one sound wave with the condensation of another reinforces the sound, it should be possible to extinguish the sound, or produce silence, by having the condensation of one wave meet the rarefaction of another. We have *interference of sound when one sound wave is so superimposed upon another that silence is produced.*

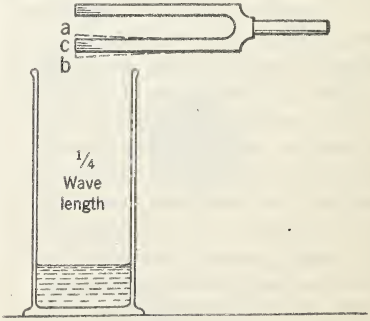


Fig. 401. Resonance produced by closed tubes.

We may demonstrate interference by repeating the experiment of the preceding section and adjusting the water level so that the closed tube is just one-eighth the wave length of the fork. Then the condensation of the direct wave meets a rarefaction of the reflected wave and reduces the loudness of the sound or extinguishes the sound entirely.

**376. How are beats produced?** Suppose that we have two sound waves of unequal length traveling in the same direction through the air or some other medium. Suppose that we plot a curve, as in Fig. 402a to represent a wave that is 4 ft. long. Then let us plot a second curve, Fig. 402b, to represent a wave 5 ft. long. We observe that in some places the two waves coincide in almost the same phase and in other places in almost the opposite phase. The straight line is used to represent the level in each case.

From a straight line in Fig. 402c we can plot a *composite* curve constructed by using the *resultants* of all the crests and troughs of the two trains of waves. At point $C$, the crests which represent sound condensations meet and the *sound is intensified*. At point $D$, a condensation coincides with a rarefaction and the *sound is diminished*, or silence may result. For these reasons, when two tuning forks of unequal vibration rates are sounded at the same time, the sound is alternately augmented and diminished. *An outburst of sound followed by an interval of comparative silence is called a beat.* The number of beats produced per second is equal to the difference between the vibration rates of the two vibrating bodies. For example, a tuning fork having a frequency of 256 will produce 4 beats per second if it is sounded with a fork whose frequency is 260, or if it is sounded with one whose frequency is 252.

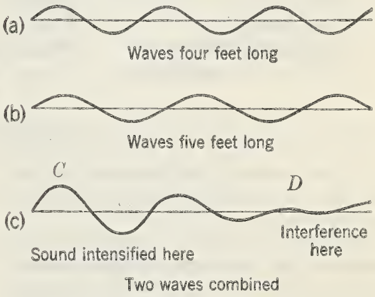


FIG. 402. Sound waves may interfere with each other.

## Summary

Sound has its origin in a vibrating body. Sound waves are transmitted to the ear through some medium. Solids are the best media for sound transmission; liquids and gases follow in the order named. Sounds do not travel through a vacuum.

The velocity of sound in air at 0° C. is 1090 ft. per sec. The velocity increases 2 ft. for a rise in temperature of 1° C. Sound travels about 4 times as fast in water as it does in air. Its velocity in solids is many times as great as in air.

Sound waves may be reflected, producing echoes. When the reflected sound wave reinforces the direct wave, resonance is produced. The best resonant length for a closed pipe is $\frac{1}{4}$ the wave length; the best resonant length for an open pipe is $\frac{1}{2}$ the wave length. Parallel walls often produce multiple echoes.

When two sound waves are so superimposed that a condensation meets a rarefaction, the sound is reduced by interference. An outburst of sound followed by an interval of comparative silence is termed a beat.

Sounds differ in loudness, pitch, and quality. Pitch depends only upon the number of vibrations that reach the ear per second. Loudness depends upon the amplitude of vibration, the area of the vibrating body, and the distance from the source of sound.

The loudness of a sound is measured by the bel or decibel as a unit. Anti-noise campaigns are now under way in many cities to reduce the number of decibels in streets.

*How many of the following terms and phrases can you define or explain?* (*"Check and double-check."*)

Ultrasonic waves
Sound insulation
Velocity of sound in air
Velocity of sound in liquids and solids
Sound ranging
Longitudinal vibrations
How sound is transmitted
Echoes
Decibels
Best resonant length
Beats
Loudness
Pitch
Stethoscope
Forced vibration
Resonance
Sources of sound
Acoustics
Sound reflectors
Sympathetic vibrations
Interference
Doppler's principle
Intensity

## QUESTIONS

1. Do sounds of different pitch travel with the same velocity? Give a reason for your answer.

2. A person standing near one end of a long iron pipe hears two distinct sounds when the other end is struck with a hammer. Explain.

3. Why does the pitch of a circular saw fall as a board is pushed into the saw?

4. Why is it difficult for one speaking in the open air to be heard?

5. At a track-meet should the timers start their watches with the flash of the pistol or with its report? Give a reason for your answer.

6. When calling to someone at a considerable distance, is "cupping" the hands before the mouth of any advantage? Explain.

7. How may echoes be of use to vessels at sea during a heavy fog?

8. How do you account for the peculiar shape of the ceilings in the waiting rooms of many railroad stations?

9. Why was it so difficult for men to cut the barbed-wire entanglements in "no man's land" without being heard by the enemy?

10. Why is it difficult for the men in the rear of a long line of soldiers to keep in time with a band in front?

11. A little dog trotting across a bridge causes it to vibrate more vigorously than a team of horses walking and drawing a heavy load. Explain.

12. Why are soldiers commanded to break step when crossing a long bridge?

13. A few years ago a dancing floor collapsed when a number of couples were dancing the Charleston. What condition may have caused the collapse?

14. Deaf children listen to music by resting their hands and heads upon the frame of a piano. Explain.

15. How can an automobile mechanic use a stethoscope to good advantage? How might he use a screw driver?

16. Why does the pitch rise as water is poured into a tall cylinder?

17. How does a piano tuner use beats in tuning a piano?

18. Explain why the echoes produced in

an empty hall usually disappear when the hall is filled with people.

19. Geologists make use of listening devices to determine how deep oil reservoirs lie beneath certain kinds of stratified rock. Can you find out how this is done?

20. What would be the advantage of a muffler on an airplane engine? What would be its disadvantage?

21. What are the ears of a submarine and of what advantage are they? Through what medium does the sound travel?

## PROBLEMS

### Group A

1. A man counts 10 seconds between the flash of lightning and the thunder crash when the temperature is 25° C. How far away did the electrical discharge occur?

2. Five seconds elapse between the firing of a gun and the return of the report. How far distant is the reflecting surface, if the temperature is 30° C.?

3. A man sets his watch by a whistle which is 2 miles distant. If the temperature is 25° C., how much will his watch be in error? Will it be too fast or too slow? If the wind is blowing with a velocity of 30 ft. per second, how will the result be affected?

4. If sound travels 1 mi. in 4.8 sec., what is the temperature of the air through which it is transmitted?

5. Two forks have vibration rates of 480 and 512 respectively. How many beats per second are heard when they are sounded simultaneously?

6. Two forks have vibration rates of 256 and 266 respectively. How many beats are heard when they are sounded simultaneously? A rubber band is placed around the prong of one of the forks, and then 15 beats per second are heard. Which fork was weighted to produce this result?

### Group B

7. A fork that makes 384 vibrations per second produces resonance with a closed tube 8.9 in. long. Find the velocity of sound. What is the approximate temperature?

8. When the temperature is 25° C., a fork vibrates 64 times per second. What is the wave length produced?

9. A closed tube is 30 cm. long. It produces resonance with a tuning fork when the temperature is 25° C. What is the wave length of the fork? What is its frequency?

10. A man drops a stone into a mine 1200 ft. deep. If the temperature is 15° C., how much time will elapse before he hears the stone strike the bottom? (Calculate both the time needed for the stone to fall and for the sound to return.)

11. A fork vibrates 256 times per second. If the temperature is 30° C., how long a closed tube will be needed to produce resonance with the fork?

12. An open tube is 2 ft. long. What is the wave length of the note with which it produces the best resonance? If the temperature is 68 ° F., what is the frequency of the note?

# *Sound — Music*

## 1. Music and Quality

**377. What is the diatonic scale?** In Section 370 we used a siren disc and forced air through each of the four rows of holes *successively*. If we use the disc again and *simultaneously* force the air through all the rows of holes except the inner one, the four notes that are produced will form a major chord. The relative frequencies of the four notes will be 24, 30, 36, and 48. If we divide each of these numbers by six, we have the simple ratios 4, 5, 6, and 8. Any three notes whose vibration ratios are 4, 5, and 6 will produce a *major triad* when they are sounded together. These three notes, with the octave above the first note, produce a *major chord*. The *major* diatonic scale is built up of three major chords. See the table at the top of the next page.

If we use 256 vibrations to represent middle C on the piano, then the table shows the vibration rates for the white keys in a little more than one octave. We find that the vibration rates for C, E, G, and C′ have ratios of 4, 5, 6, and 8. They form a major chord. Another major chord is formed by the notes G, B, D′, and G′, and a third by the notes F, A, C′, and F′.

The note C′, which is one octave above middle C, has a vibration rate just twice as great as that of C. The frequency of a note an octave above another is always twice the frequency of the note of lower pitch. Doubling the frequency raises the pitch one octave. From the table, we see that the frequency of D is $\frac{288}{256}$, or $\frac{9}{8}$ times that of C. Of course, D in this table is just $\frac{1}{2}$ the frequency of D′, an octave higher. The vibration rate of E is $\frac{320}{256}$ of C, or $\frac{5}{4}$; F is $\frac{341}{256}$, or $\frac{4}{3}$; G is $\frac{384}{256}$, or $\frac{3}{2}$; A is $\frac{426}{256}$, or $\frac{5}{3}$; and B is $\frac{480}{256}$, or $\frac{15}{8}$. C′ is $\frac{512}{256}$, or $\frac{2}{1}$. (See Fig. 403.)

In the next octave, we find that D′ is $\frac{9}{8}$ times the frequency of C′, the first note in the octave, or the key-note.

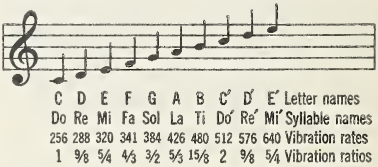

C D E F G A B C′ D′ E′ Letter names
Do Re Mi Fa Sol La Ti Do′ Re′ Mi′ Syllable names
256 288 320 341 384 426 480 512 576 640 Vibration rates
1 9/8 5/4 4/3 3/2 5/3 15/8 2 9/8 5/4 Vibration ratios

FIG. 403. The major diatonic scale. Key of C.

### Vocabulary

**Chromatic**, colored; shades of tone analogous to shades of color.

**Overtone**, a note whose vibration rate is a whole number multiple of its fundamental.

**Orthophonic** (*orthos*, straight; *phonein*, to sound), reproducing more nearly the quality of the original.

**Vibrograph**, a device used to show sound waves graphically.

**Harmony**, a combination of notes that is pleasing.

**Discord**, a combination of notes that is harsh or unpleasant.

**Timbre**, the quality of a tone.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Syllables | do | re | mi | fa | sol | la | si | do | re |
| Letters | C | D | E | F | G | A | B | C′ | D′ |
| Vibration rates | 256 | 288 | 320 | 341 | 384 | 426 | 480 | 512 | 576 |
| Relative vibration rates | 24 | 27 | 30 | 32 | 36 | 40 | 45 | 48 | 54 |
| Chord (tonic) | 4 | | 5 | | 6 | | | 8 | |
| Chord (dominant) | | | | | 4 | | 5 | | 6 |
| Chord (subdominant) | | | | 4 | | 5 | | 6 | |

($\frac{576}{512} = \frac{9}{8}$.) In the same manner we can find the frequency of any note in this octave by multiplying the vibration rate of the keynote by the ratios just given. For example, the frequency of E′ equals $\frac{5}{4} \times 512$, or 640. We could also find the vibration rate of E′ by doubling the vibration rate of E (320).

**378. What is the chromatic scale?** Suppose we use D as the keynote and multiply its frequency (288) by $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$ and 2 in turn. The table given at the foot of this page shows the results obtained when compared with the notes of the key of C.

We observe that there is considerable variation, especially in the vibration rates of F and C′. The difference is so great that two new notes, F♯ (F sharp) and C♯, are used by the musician when he plays in the key of D. The notes E and A are not exactly the same, but no new notes are added here.

The vibration rate of F sharp, or F♯, is obtained by multiplying the frequency of F by $\frac{25}{24}$; if a note in the chromatic scale is to be flatted, its frequency is $\frac{24}{25}$ that of the note itself. These intervals are called *chromatic semitones*. They are represented by the black keys on the piano. By using different letters as keynotes, we find that five new notes, called flats or sharps, must be added to each octave.

**379. What is the tempered scale?** In building up the chromatic scale, we learned that five new notes must be added to the diatonic scale in each octave. If we examine the two scales given for the keys of C and D, we note that there is a difference of 4 vibrations for the note E and about 6 for the note A. If all the possible keys were built up in the same manner and new notes added where any difference exists, a large number of additions would be needed. The black keys on the piano are used either as the sharp of the note below or as the flat of the note above. In the chromatic scale there is a difference between C♯ and D♭ (D flat). For example, $\frac{25}{24}$ times 256 equals 266 vibrations, or C♯; and $\frac{24}{25}$ of 288 equals 276 vibrations, or D♭. Putting in new notes with their sharps and flats wherever even slight variations occur would give an octave of about 70 notes. The difficulty in learning to play a piano or organ having 70 notes in each octave is obvious; it is so impractical that a system of equal temperament has been devised. It is a compromise scale. There are twelve *intervals* in the octave, including sharps and flats, and the vibration rate of C′

| | C | D | E | F | G | A | B | C′ | D′ |
|---|---|---|---|---|---|---|---|---|---|
| Key of C | 256 | 288 | 320 | 341 | 384 | 426 | 480 | 512 | 576 |
| Key of D | - | 288 | 324 | 360 | 384 | 432 | 480 | 540 | 576 |

is just twice that of C. By extracting the twelfth root of 2, we get an equal interval for each semitone.

$$\sqrt[12]{2} = 1.05946.$$

In the tempered scale the vibration rate of any note can be obtained by multiplying the frequency of the preceding note by 1.05946. The equally tempered scale is used in playing most musical instruments. A skillful violinist, however, may produce better music by using the true intervals of the diatonic scale. A comparison of the two scales is shown in Fig. 404. The difference is not very great in any case. In fact few persons can tell a difference in pitch of only 2 or 3 vibrations per second.

**380. What is standard pitch?** The middle C tuning forks that are used in all physical laboratories are all tuned to 256 vibrations per second. This gives A 427 vibrations per second. In *concert* pitch, which is now little used, middle C has 271 vibrations per second. *International* pitch differs slightly from that used by physicists in the diatonic scale, since A equals 435 vibrations per second. With the pitch adopted by the American Federation of Musicians, A has 440 vibrations per second. Sopranos find it difficult to sing music written by Handel and his contemporaries when accompanied by instruments tuned to the pitch adopted by the American Federation of Musicians.

**381. How do noise and music differ?** Many siren discs have four rows of evenly spaced holes, and one row of holes that are irregularly spaced. If we force a blast of air through any one of the regularly spaced holes, a *musical note* is produced. (See Fig. 399.) If we force air through the irregularly spaced holes, a *jarring noise* is produced. In music, the pulses reach the ear in rather regular succession. Striking the desk with a stick, scraping the feet over the floor, or dropping the dinner dishes will set up irregular vibrations. Sounds produced in that manner cause noise, but not music.

**382. What causes harmony and discord?** If we strike the notes C and E of a piano at the same time, the two notes are pleasing. They are said to produce *harmony*. When the notes C and D are struck simultaneously, the sound is displeasing and *discordant*. In the first case, there are 64 beats per second. They are so close together that the ear does not distinguish between them, and harmony is produced. When C and D are struck at the same time, there are 32 beats per second. This number of beats per second causes about the worst possible discord.

To show that the number of beats heard per second determines whether a sound will be pleasing or unpleasant, we may use two singing flames and

| CHROMATIC SCALE | | TEMPERED SCALE | |
|---|---|---|---|
| C | 256 | C | 256 |
| C♯ | 266.6 | C♯ or D♭ | 271.2 |
| D♭ | 276.5 | | |
| D | 288 | D | 287.3 |
| D♯ | 300 | D♯ or E♭ | 304.4 |
| E♭ | 307.2 | | |
| E | 320 | E | 322.5 |
| F | 341.3 | F | 341.7 |
| F♯ | 355.5 | F♯ or G♭ | 362 |
| G♭ | 368.6 | | |
| G | 384 | G | 383.6 |
| G♯ | 400 | G♯ or A♭ | 406.4 |
| A♭ | 409.5 | | |
| A | 426.6 | A | 430.5 |
| A♯ | 444.4 | A♯ or B♭ | 456.1 |
| B♭ | 460.8 | | |
| B | 480 | B | 483.3 |
| C′ | 512 | C′ | 512 |

FIG. 404. Comparison of two musical scales.

change the vibration rate of one of them gradually. We connect two jet tubes to a gas-cock as shown in Fig. 405. We then support two glass tubes about 1 in. in diameter and 16 to 18 in. long over the jet tubes. The flames will yield a singing noise when adjusted to the proper height. If we slide a paper cylinder over one of the tubes to change its length, the two flames will have different vibration rates and beats can be heard. When only a few beats per second are heard, the sound is not displeasing. By varying the length it is possible to produce about 30 beats per second, and the noise heard is jarring and discordant. If the number of beats is increased to 64 or more, the two notes are harmonious.

**383. Is there a limit to the number of vibrations which the ear can hear?** If we wave our arms, for example, no sound is heard. The vibrations are too slow to affect the auditory nerve. It is found that at least 16 vibrations per second are needed to produce sound that is audible to the human ear. Such a number represents the *lower limit of audibility.* Of course, persons vary in their ability to hear sounds of low pitch. The lowest note of the ordinary piano makes about 27 vibrations per second. It is said that the ears of some persons are not sensitive to this note. A note of very low pitch may be produced by pressing the forefingers against the ears and then closing the other fingers firmly and quickly.

On the other hand, the vibrations may be so rapid that the ear is not sensitive to the very short waves produced. The frequency which marks the upper limit of audibility varies with the individual, but the maximum frequency capable of being perceived by any human ear seems not to exceed 38,000 to 40,000. In many cases, it is much below that number. The auditory nerves of some persons do not seem to be tuned to receive notes of very high or very low pitch, just as some eyes are not sensitive to certain colors. It is not a matter of loudness, but of pitch. The shrill chirp of a cricket is said to be inaudible to some persons.

In radio we use the terms *radio-frequency* and *audio-frequency.* Notes of audio-frequency are capable of affecting the ear. Frequencies below 10,000 per second are spoken of as audio-frequencies, because they are audible in a telephone receiver.

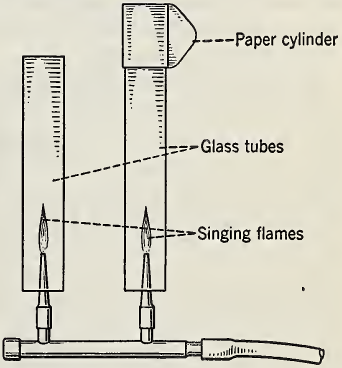


Fig. 405. Beats may be produced by singing flames.

## 2. Quality

**384. What is meant by the fundamental?** If a rather long string is plucked or bowed, it is sometimes possible to see it vibrating. If it is plucked in the middle, it will vibrate *as a whole.* (See Fig. 406.) When a string vibrates

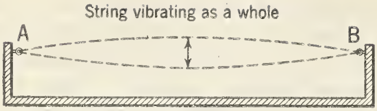


FIG. 406. A string vibrating as a whole sounds its fundamental.

as a whole, it produces a note of its lowest possible pitch. Such a note is called its *fundamental.*

The *sonometer* is an instrument much used in physical laboratories for testing the vibrating rate of strings and for showing how they vibrate. It consists of two or more strings stretched over a sounding board. The strings may be varied in diameter, material, or in tension. (See Fig. 407.)

When a string is plucked, struck, or bowed near one end, it may vibrate in several parts or *segments,* with nodes, or places of no vibration between the segments. (See Fig. 408.) Stranger still, it is possible for a string to vibrate as a whole and in parts at the same time, as represented by Fig. 409.

**385. What are overtones?** Suppose we divide a sonometer string into eight equal parts and place V-shaped paper riders on the string in the positions shown at 1, 2, 3, 4, and 5, as in Fig. 410. If we touch the string gently at *C* and bow it at *D,* the paper riders at the positions 1, 3, and 5 will be thrown off. Those at 2 and 4 are not disturbed. This proves that the string is now vibrating in four equal parts or segments, with nodes at positions 2 and 4. Making a node at *C* by touching the string also causes nodes to be formed at the two other positions. If one were to touch the string at a position one-third its length from one end, it would then vibrate in three segments.

One of the most interesting things about this experiment arises from the fact that the pitch of the vibrating segment is two octaves higher than that of the fundamental. The new note is called an *overtone. A note whose vibration rate is a whole number multiple of that of the fundamental is called an overtone,* or *harmonic.* When a string vibrates in two segments, the overtone produced is an octave above the fundamental. For example, the first overtone of a C string is C′, a note of just double the vibration rate of C. (256 × 2 = 512.) The second overtone of C has a frequency three times that of C. 256 × 3 = 768. A note having 768 vibrations per second corresponds to G′. The third overtone of C has four times its frequency. 256 × 4 = 1024, the note C″. The fourth overtone of C is E″, whose vibration rate is 1280. (256 × 5.)

**386. Upon what factors does quality depend?** Two persons may be singing true to pitch, but the voice of one of them may be more pleasing. It is possible, too, to pick out the various instruments in an orchestra, even when the pitch is the same and they are all equally loud. We say that the *quality* differs. Let us bow a string near the

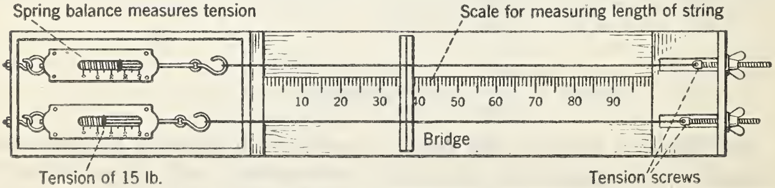

Spring balance measures tension
Scale for measuring length of string
10
20
30
40
50
60
70
80
90
Bridge
Tension of 15 lb.
Tension screws

FIG. 407. The sonometer is used to study the laws of strings.

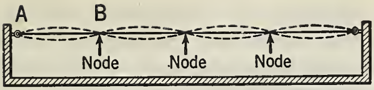


Fig. 408. A string may form loops and nodes as it vibrates.

middle to throw it into vibration. It will then sound its fundamental. While it is vibrating, let us touch the string very *lightly* in the middle. The string still continues to vibrate as a whole and we can hear the fundamental. But it will also vibrate in two segments at the same time and the tone will be richer and fuller because we can also hear the *first overtone.* The quality of the tone is improved by the addition of the overtone to the fundamental. *The quality of a sound depends upon the number of overtones present and upon their prominence.*

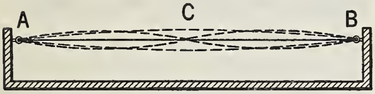


Fig. 409. Overtones are produced when a string vibrates in two or more segments.

In musical instruments, the strings are plucked, bowed, or struck near one end instead of in the middle. Thus overtones are produced which blend with the fundamental and produce richer and fuller tones.

Certain overtones are displeasing to the ear, since they produce notes that do not correspond to the musical scale. The sixth overtone is especially displeasing. Hence pianos are so constructed that the hammers strike the strings about $\frac{1}{7}$ of their length from the end. Then the string cannot vibrate in seven segments and produce the sixth overtone, which would be discordant.

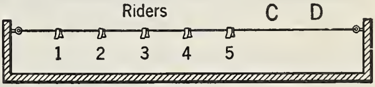


Fig. 410. Paper riders show that a string vibrates in segments.

## 3. Laws of Strings

**387. What laws govern the vibration of strings?** If we examine a piano, we find that the bass strings are longer, thicker, and looser than those of the treble. Their density is also made greater by winding them with copper wire We must bear in mind that the bass string has a low frequency and that the treble string vibrates rapidly. In the construction of the piano we have examples of all the methods used to control the frequency of strings.

By the use of a sonometer, Fig. 407, several facts concerning the factors which affect the frequencies of vibrating strings have been learned. They are usually spoken of as the *laws of strings,* and they may be stated as follows:

1. *Law of lengths.* When we wish to increase the pitch of any stringed instrument, we may shorten the length of the string. A violinist shortens the A string of his violin about one inch when he wishes to produce the note B. *The vibration rate of a string is inversely proportional to its length,* if its diameter, density, and tension remain unchanged.

Problem. If the D string of a violin is 12 in. long, how much must it be shortened to produce the note E?

*Solution.* D corresponds to 288 vibrations per second, and E has a frequency of 320. Then, $288 : 320 = x : 12$. Therefore, $x = 10.8$ in., the length of a string which vibrates 320 times per second. The D string must be shortened 1.2 in. to produce the note E.

2. *Law of diameters.* On a guitar or harp, the strings that produce the notes of higher pitch are of smaller diameter. This is true of other stringed instruments. A string 0.1 in. in diameter will vibrate just twice as fast as a similar string 0.2 in. in diameter. *The vibration rate of a string is inversely proportional to its diameter,* if its length, density, and tension are constant.

3. *Law of tensions.* When one tunes a violin or other stringed instrument, he tightens the strings to increase the frequency. It has been proved by experiment that *the vibration rate of a string is directly proportional to the square root of the tension on the string,* if all other factors are constant.

PROBLEM. A string stretched with a force of 9 lb. produces the note C; with what force would the same string have to be stretched to produce the note C′?

*Solution.* C has a frequency of 256, and C′ a frequency of 512. Then, $256 : 512 = \sqrt{9} : \sqrt{x}$. Whence, $x = 36$ lb.

4. *Law of densities.* The heavier a string is, the more slowly it vibrates. For this reason, some strings are made of dense material, and other strings are wound with dense material to make the strings vibrate slowly. *The frequency of a vibrating string is inversely proportional to the square root of its density, if other factors are constant.*

## 4. Musical Instruments

**388. What are stringed instruments?** In a very large number of musical instruments the sound waves come from vibrating strings. The piano, violin, guitar, ukulele, mandolin, and harp are common examples. In each case some form of sounding board is used. The thin string does not have sufficient area to furnish the required volume of sound, but it forces the sounding board into vibration, even if their natural vibration rates are unequal. Thus the sound is intensified. Pairs of strings are used for certain octaves of the piano to give greater volume; in the treble, three strings are used for each note.

**389. How do organ pipes produce sound?** To produce the sound in an organ pipe, a stream of air is usually directed against one edge of an opening in the pipe. (See Fig. 411.) This produces a vibrating air jet whose frequency is controlled by the length of the pipe, since the vibration rate of the air jet is influenced by the return of

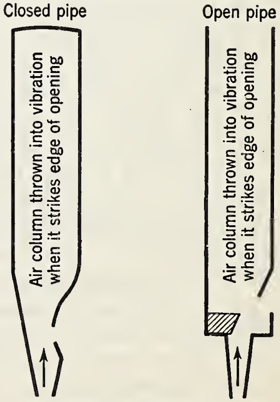

Closed pipe
Open pipe
Air column thrown into vibration when it strikes edge of opening
Air column thrown into vibration when it strikes edge of opening

FIG. 411. Organ pipes.

the reflected air pulses. For example, a *closed organ pipe produces a note whose wave length is four times as long as the pipe itself.* A closed pipe one foot long produces a note whose wave length is four feet. *An open pipe produces a sound wave which is twice the length of the pipe itself.* Hence, *an open pipe produces a note an octave higher than a closed pipe of the same length.*

To construct a set of organ pipes, their lengths must be made *inversely* proportional to the vibration ratios as given in Section 377. For example, the pipes used to sound the notes of one octave, beginning with C, would have the following ratios: 1; $\frac{8}{9}$; $\frac{4}{5}$; $\frac{3}{4}$; $\frac{2}{3}$; $\frac{3}{5}$; $\frac{8}{15}$; and $\frac{1}{2}$. To summarize, the *pitch of a pipe varies inversely as its length.*

**★390. What overtones can pipes produce?** When a pipe is blown gently, it usually sounds its fundamental only. Overtones are produced by blowing harder, since in such cases the air column vibrates in loops. If the pipe is closed, there will always be a node at the closed end of the pipe and a loop or anti-node at the other end. The only overtones possible with closed pipes are those whose vibration rates are *odd* multiples of the fundamental. Hence, the first overtone of a closed C organ pipe is not C′, but G′, a note whose vibration rate is 3 (an odd number) times that of the fundamental. The next overtone is E″, whose frequency is 5 times that of C.

With open pipes there is a node in the middle and a loop or anti-node at each end. For that reason, the whole series of overtones is possible with open pipes. The first overtone of a C open pipe is C′, the second overtone is G′, and the third overtone is C″.

When a hole is bored in a pipe, it produces the same effect as if the pipe were cut off at that point. A loop or anti-node is produced at the opening. Wind instruments of nearly all kinds have several holes so that the length may be varied to produce notes of varying pitch. Such holes may be closed again by the finger or by means of a valve.

**391. How does the Hammond organ work?** Without the use of pipes, this instrument produces the effects of the pipe organ. The tones are first created as electric waves and then amplified into sound waves. Tone wheels about as big as a silver dollar generate the electric waves. On the rim of the wheel there are regularly spaced bumps similar to the teeth on a gear wheel. As these wheels rotate at constant speed they come close to small magnets, each of which is wound with a coil of wire. Thus they disturb the magnetic field and set up tiny electric currents in the coil. These currents are then changed into sound waves. All the tone wheels are geared together and turned by a motor. (See Fig. 412.)

Suppose that one of the wheels is rotating at such a speed that 440 bumps pass the magnet and its coil per second. Then 440 electrical impulses are set up in the coil each second. When they are amplified and changed into sound waves, the note corresponding to 440 vibrations per second is produced. There is a separate tone wheel for each note or frequency used

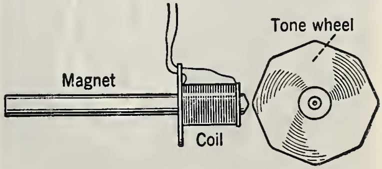
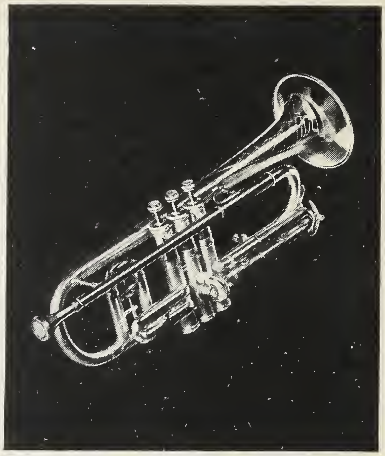


Fig. 412. Magnet and tone disc as used in the Hammond organ.

in a Hammond organ. The volume is controlled by means of a speaker and amplifying tubes in a tone cabinet, not so very different from radio. It is possible, too, to reproduce the tone of various wind instruments on the organ.

**392. How do wind instruments produce sound?** In many wind instruments, a vibrating air jet is the source of sound. The air jet may be produced by a vibrating reed as in the organ, harmonica, accordion, clarinet, or saxophone. Some organ pipes have a vibrating reed. A bellows is sometimes used to throw the reed into vibration. (See Fig. 413.)

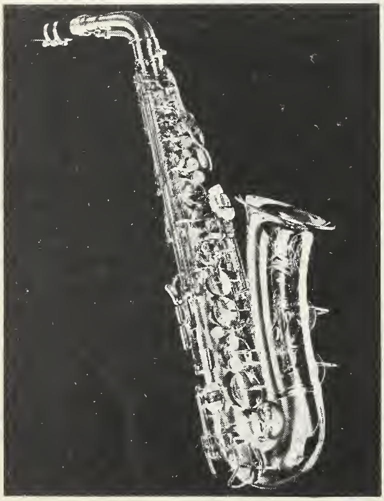
In the flute, fife, and piccolo the vibrating air jet is produced in the same manner as in the organ pipe. A stream of air is directed against the edge of an opening near one end of the instrument. The pitch is regulated by the length.



*Courtesy of C. G. Conn, Ltd.*

FIG. 414. The cornet.

In the cornet, trombone, and bugle the lips of the player vibrate. The frequency depends upon the length of the tube. In the cornet, openings regulated by valves produce variations in pitch by changing the length of the pipe. (See Fig. 414.)



*Courtesy of C. G. Conn, Ltd.*

FIG. 413. The saxophone.

**393. How do the vibrations of bells and plates produce sound?** When bells and plates vibrate, notes are produced which are not whole number multiples of the *fundamental*. Although they are not whole number multiples of the fundamental, yet they are called overtones. For this reason chimes are played by striking the bells in *succession*. Fig. 415 shows some complex figures produced by bowing a metal plate covered with fine sand. Nodes may be formed at various positions by touching the edge of the plate with the thumb and finger. In each case the

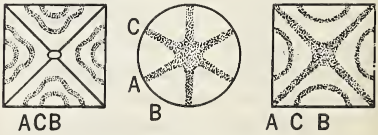


FIG. 415. Vibrating plates.

plate is touched at $A$ and $C$ to produce nodes; it is bowed at $B$. The irregularity of the curves shows why it is quite impossible to have such plates produce harmony by *simultaneous* vibrations. The patterns produced in this way are used as designs for wallpaper.

**394. How do vibrating membranes produce sound?** In some musical instruments, the vibrating part is a membrane. The tambourine, drum, and kettle drum are examples. The human voice is produced by the vibration of membranes. Two folds of ligamentous membrane which are stretched across the larynx, or Adam's apple, form the vocal cords. By the contraction of certain muscles these cords may be tightened at will. Variations of the tension produce notes of different pitch. In speaking, one learns to modulate his voice by varying the position of his tongue, palate, teeth, and lips. The quality of the voice depends upon the overtones which are made prominent by resonance. By cultivation, a person may learn to suppress certain harsh overtones and reinforce others which are more pleasing.

**395. What is the principle of the phonograph?** This instrument is one of the many inventions of the American inventor, Thomas A. Edison. In the early types, a disc having an elastic membrane carrying a steel needle or stylus was attached to a mouthpiece. When one spoke or sang into the mouthpiece, the vibrations produced by the voice forced the disc to vibrate correspondingly. In the meantime, the stylus recorded the vibrations by cutting a zigzag groove in tinfoil wound on a cylinder. Later, a wax cylinder was used to receive the impressions. In many cases the stylus traces its zigzag path over a greased metal disc. This metal disc is then etched, and a master record made from it by plating a copper electrotype upon it. Such a master record has tiny ridges which conform to the grooves of the original record. Hundreds of copies of the original record can be made by pressing the master record into gutta-percha, hard rubber, condensite, or some composition material.

To reproduce the sound, the disc record is placed upon a turntable driven by some type of motor or spring. A needle which follows the groove in the record acts as a lever to throw into vibration the diaphragm to which the other end of the needle is attached. (See Fig. 416.) The diaphragm is made of mica, duralumin, or several sheets of rice paper shellacked together. The quality of the tone produced depends largely upon the needle used and upon the resonance of the amplifying horn of the instrument.

**396. How does the dictating machine work?** This machine is a modifi-

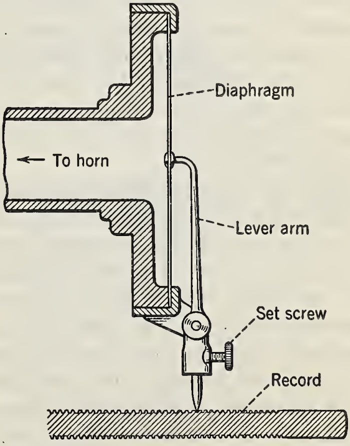
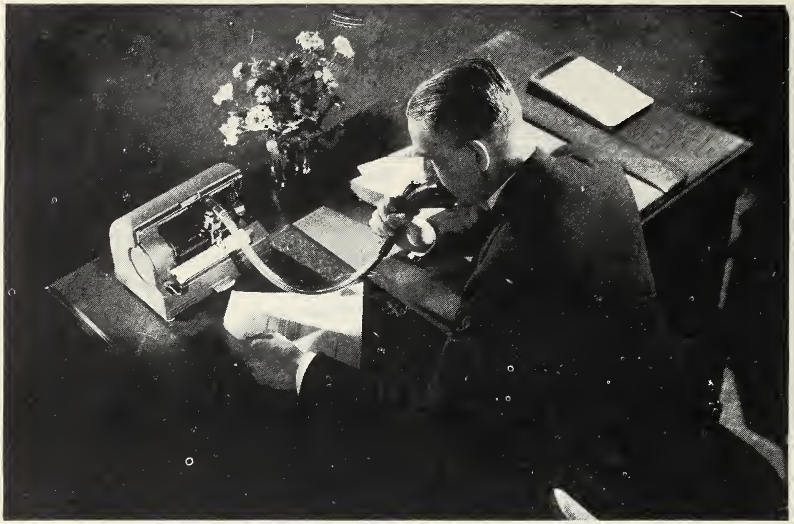


FIG. 416. A phonograph reproducer.



Courtesy of Thomas A. Edison, Inc.

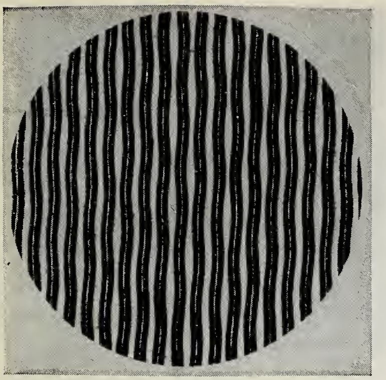
FIG. 417. The dictating machine makes a record which can be reproduced at any time.

cation of the old type of phonograph. Under the name "Dictaphone" or "Ediphone" it finds extensive use in offices. An official at his desk speaks into a mouthpiece, and his words are recorded upon a hard wax revolving cylinder. Later, the wax cylinder is removed by a secretary who transfers it to a reproducing machine. Through small tubes leading to her ears, she listens to the dictation, and possibly types the message at the same time. (See Fig. 417.)

**★397. How are records cut electrically?** The old mechanical methods of cutting records did not give very satisfactory results. The vowel sounds were of fairly good quality, but the consonants were not so perfectly reproduced. The "s" and "sh" sounds of speech were lacking. Then, too, the lower bass notes of music were lacking, because the older records included only those frequencies between middle C and G''', or from 250 to 3000 vibrations per second.

Now, nearly all records are cut electrically by a process developed by the engineers of the Bell Telephone Laboratories. The sound waves are picked up by means of a special microphone which converts them into pulsating or fluctuating electrical currents. These currents are amplified and then operate an electro-magnetic recorder which cuts the record in a disc of soft wax. This method of cutting records enables the operator to control the amplification, and it cuts the record accurately, including frequencies ranging from 35 to more than 10,000 vibrations per second. (See Fig. 418.)

In reproducing such records, the sound waves are taken up through a needle and a microphone which converts the sound waves into electrical currents. Such currents are amplified and then changed back to sound waves



*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 418. Photomicrograph of an electrically cut record.

again by means of a loud speaker. All audible frequencies are reproduced by such methods.

**398. How can sound waves be shown graphically?** Several methods have been used to represent sound waves graphically. A few are given as follows:

1. *The vibrograph.* In this instrument a stylus is fastened to one of the prongs of a tuning fork, the stem of which is held firmly. The fork is then thrown into vibration and a piece of smoked glass is drawn beneath the fork so that the stylus traces its vibrations on the smoked glass. A smoked cylinder may be used in a similar manner to record the vibrations. (See Fig. 419.)

2. *The manometric flame.* This method was devised by Koenig. In the *manometric flame apparatus* of Fig. 420, an elastic membrane separates the two compartments of a metal block. One of the two openings to the left-hand compartment is fitted with a jet tube for use as a gas burner; the other opening is connected to a gas-cock. The right-hand compartment has a single opening fitted with a funnel tube. The sound waves which enter this tube produce corresponding vibrations in the elastic membrane. The condensations of the sound waves compress the gas and make the gas flame higher. The rarefactions permit the gas to expand and the flame is lowered. The fluctuations in the gas flame, which correspond to the sound waves, cannot be seen unless they are viewed in a revolving mirror, which spreads them out. When no sound waves enter, the revolving mirror shows a band of light. If a note sounding its fundamental is used with the instrument, there will be a series of zigzag lines, all of the same length. When overtones are produced with the fundamental, the lines are of varying length.

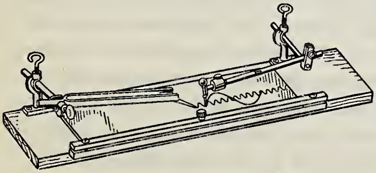


FIG. 419. The vibrograph is used to study sound waves.

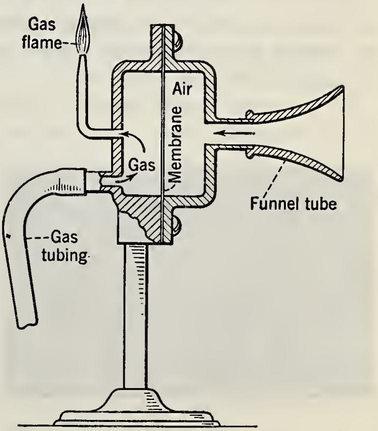


FIG. 420. A manometric flame apparatus.

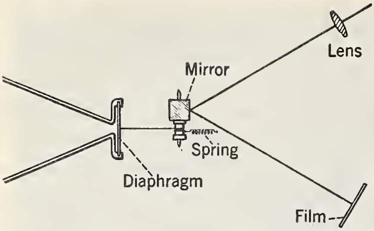


FIG. 421. The phonodeik as devised by Dayton C. Miller.

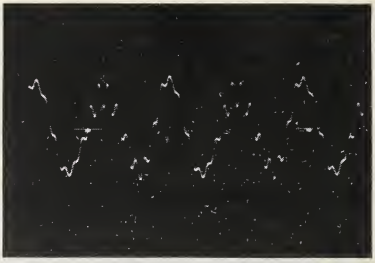

*Courtesy of Dayton C. Miller, Case School of Applied Science*

FIG. 423. The vowel sound *ee* as in *feed*. Note the overtones.

3. *The phonodeik.* This instrument was invented by Dr. Dayton C. Miller of the Case School of Applied Science. By its use it is possible to photograph the wave forms of various instruments, or of the human voice. (See Fig. 421.) The tiny mirror is free to oscillate on a small steel shaft which is mounted in jeweled bearings. A thin glass diaphragm is set in the horn of a resonator. One end of a thread is attached to this diaphragm. The thread is then wrapped around a small pulley mounted on the mirror shaft, and the other end of the thread is then fastened to a tension spring. A narrow pencil of light is focused upon the mirror by means of a convex lens. From the mirror it is reflected to a sensitized photographic film which moves at right angles to the mirror. (See Fig. 422.)

As the sound waves enter the horn of the resonator, they throw the diaphragm into vibration. The vibrations are transmitted through the thread to the mirror, causing it to oscillate on its axis. The pencil of light, reflected from the oscillating mirror, traces upon the film the sound waves that act upon the diaphragm. (See Figs. 423 and 424.)

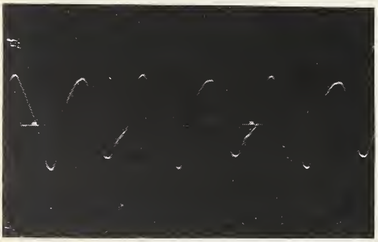
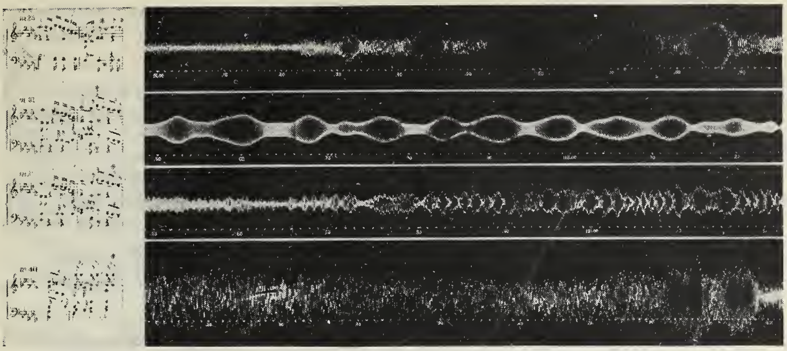

*Courtesy of Dayton C. Miller, Case School of Applied Science*

FIG. 422. The vowel sound *oo* as in *mood*.

4. *The oscillograph.* An interesting demonstration at the Century of Progress exhibition made it possible for a person to see his own voice waves. When the demonstrator spoke into a microphone, the voice waves were reproduced upon a moving screen. The oscillograph is discussed more fully in a later chapter.

**★399. How can we analyze sounds and reproduce them?** A set of resonators for use in analyzing complex sounds was devised by Helmholtz, a German physicist. The series consists of a set of hollow spheres, of such size that each one produces resonance with a note of certain pitch. (See Fig. 425.) By placing the large opening near a body producing complex sounds and holding the small opening to the ear, it is possible to pick out all the overtones that are present, if a series of resonators is used one after another.

After complex sounds have been analyzed by the use of resonators, they



Courtesy of *Dayton C. Miller, Case School of Applied Science*

FIG. 424. This figure shows sound vibrations from the singing of the Sextette from Lucia. The top line, music as sung by Caruso. The second line, as sung by Tetrazzini. The third line, as sung by Tetrazzini and Amati. The bottom line shows the vibrations produced by the entire sextette. The numbers show the time of exposure of film in tenths of seconds. Dr. Miller's phonodeik photographs the sound vibrations and enables us to study the fundamentals and overtones produced by the voices of renowned artists.

can be reproduced by using electrically driven tuning forks to represent all the different frequencies that were found to be present in the complex sound waves. Some of the vowel sounds have been reproduced by such methods.

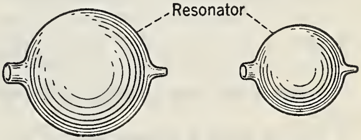


FIG. 425. Helmholtz resonators.

## Summary

The major chord is built up of notes whose frequencies have the ratios 4, 5, 6, and 8. The major diatonic scale consists of eight notes in each octave for any given key. The chromatic scale adds five notes per octave. In the equally tempered scale, the interval is uniform; the twelfth root of two is used.

Discord is a phenomenon of beats. About 30 beats per second produce the worst possible discord. If fewer than 5, or more than 60 beats reach the ear per second, the notes are not discordant.

A string vibrating as a whole produces its fundamental, or the note of lowest pitch that it can give. A frequency which is a multiple of the fundamental is called an overtone.

The frequency of a vibrating string is inversely proportional to its length, its diameter, and the square root of its density; it is directly proportional to the square root of the tension.

In musical instruments, the sound waves are generally caused by vibrating strings, or air jets. Air jets may be set up by reeds, by the vibrations of the lips of the player, or by the air striking the edge of an opening.

A closed organ pipe is one-fourth as long as the sound wave which it produces; an open pipe is one-half as long as the sound wave which it produces.

In an open pipe, the whole series of overtones is possible; in a closed pipe, only those overtones whose frequencies are *odd* multiples of the fundamental are possible.

The overtones of bells and plates are not whole number multiples of the fundamental. They do not produce harmony when struck simultaneously.

Complex sounds may be analyzed graphically by the manometric flame; the Helmholtz resonators are also used to pick out the overtones in complex sounds.

*How many of the following terms can you define or explain?* (*Are you learning to be scientific?*)

Diatonic scale
Tempered scale
Quality
Overtone
Organ pipes
Wind instruments
Phonograph
Electrically cut records
Analysis of sounds
Chromatic scale
Limits of audibility
Fundamental
Laws of vibrating strings
Stringed instruments
Hammond organ
Dictating machine
Phonodeik
Manometric flames

## QUESTIONS

1. What is the first overtone of C? Of G? Of E′?

2. Why is there a discord when C and B are struck at the same time?

3. What is the vibration rate of the sixth overtone of C? To what letter on the scale does it correspond? Why is it desirable to suppress the sixth overtone?

4. Why is a violin string bowed near one end instead of in the middle?

5. How is the pitch varied in ordinary whistling?

6. Do sound waves ever cast shadows?

7. Why does pressing the soft pedal of a piano decrease the loudness? Is the mechanism for softening the same with upright and grand pianos? Explain.

8. Does pressing either the loud or soft pedal of the piano affect the pitch of the notes? Explain.

9. Several notes may be blown on a bugle of unvarying length. Explain.

10. How does opening the holes of a saxophone or clarinet affect the pitch?

11. Why does increasing the speed of a phonograph raise the pitch?

12. Why does a short phonograph needle make the sound louder? (The student should observe that the phonograph needle is really a lever.)

13. How is the quality of the human voice modified? Where is the resonance produced?

14. A piano is properly tuned at 70° F. Is it in tune when the temperature rises to 80° F.? Explain.

15. What laws of strings are exemplified in the construction of a violin? Which law is illustrated in the tuning of stringed instruments? Which law does one use as he plays a stringed instrument?

16. When a large sea shell is held to the ear, a roaring noise is generally heard. Explain.

17. Why do windows sometimes rattle when the low notes of a pipe organ are sounded? Do you think they might be broken in such a manner?

18. Look up the subject of ultrasonic waves by use of *Reader's Guide*, and make a report to class on the topic.

19. Is it possible for a violinist to use the diatonic scale when playing a violin if unaccompanied?

20. Why are three strings used in a piano for each note in the treble?

## PROBLEMS

### Group A

1. Compare the frequencies of two strings. A is one meter long and has a diameter of 0.5 mm. B is 50 cm. long and 1 mm. in diameter.

2. A string stretched by a force of 25 kgm. gives the note E. What stretching force is needed to yield the note G?

3. A string 27 in. long produces the note C. Find the length of a similar string that will produce the note G. The note A.

4. How long must a closed pipe be to give the note G, if the velocity of sound is 1130 ft. per second? To produce the note E′? To produce the note G′?

5. A string 40 cm. long produces the note E, 320 vibrations per second. How much must the string be shortened to produce the note C′, 512 vibrations per second?

### Group B

6. Calculate the frequency and the wave length of the lowest note on the piano, $A_4$, a little more than three octaves below middle C, when the temperature is 20° C.

7. Calculate the frequency and the wave length of the highest note of the piano, C″ ″, when the temperature is 20° C.

8. Calculate the vibration rate of the first overtone of an open pipe that gives the note C′. Of the third overtone.

9. What is the frequency of the first overtone of a closed C′ organ pipe? Of the second overtone?

10. The frequency of a string 40 cm. long, 1 mm. in diameter, and stretched by a force of 36 kgm. is 400. Calculate the frequency of a second string of the same material 100 cm. long, 0.75 mm. in diameter, and stretched by a force of 64 kgm.

11. Compare the relative frequencies of two strings. One string is 150 cm. long, 1.5 mm. in diameter, has a sp. wt. of 8.8, and is stretched by a force of 64 lb. The other string is 75 cm. long, 1 mm. in diameter, has a sp. wt. of 7.6, and is under a tension of 144 lb.

# Unit Eight

# *Light*

## Preview

IT SEEMS A STRANGE PARADOX TO SAY THAT PHYSICISTS are in greater darkness concerning the true nature of light than they are in regard to almost any other topic. At best we now have only theories. Such theories have changed, as theories nearly always do, from one period to another. We find the great philosopher Sir Isaac Newton advocating strongly the corpuscular theory, according to which bodies that emit light were believed to send out a stream of minute particles called corpuscles. But it is impossible to explain the refraction of light or the interference of light by such a theory.

The wave theory proposed by Huygens was bitterly attacked, and its opponents asked what medium can transmit light waves through a vacuum. Then Huygens invented from his own imagination the ether as the transmitting medium. Whether we accept the ether or not, yet it is true that the wave theory of light offers a simple explanation of refraction and interference.

But some facts concerning light cannot be explained by the wave theory alone. Max Planck proposed his quantum theory, which seems to include a partial return to the corpuscular theory. At present, the physicist finds that he needs to have a kind of combination of the two theories to explain all the phenomena of light.

In elementary physics, however, we are most concerned with the effects which light produces. We can measure its velocity and its intensity. In the study of the intensity of light, we shall interest ourselves in the distribution of light and the number of foot-candles needed for various kinds of work.

We need to study mirrors, too, in order to learn how they reflect light and form images. Man has learned how to use lenses to magnify small objects, to correct his impaired vision, or to bring distant objects close enough to be seen more easily. Then, too, we live in a world of color. Compound light can be analyzed and monochromatic colors may be combined to produce polychromatic light. In efforts to prevent glare, scientists are becoming more and more interested in the polarization of light.

# Light

## 1. Nature and Velocity

**400. What is the nature of light?** We know that sound is transmitted to our ears by means of waves traversing some medium. We have learned, too, that radiant heat energy is believed to be transmitted by a medium called the ether. At the present time, some scientists believe that other ether waves produce various other effects. Some ether waves affect our radio sets and make wireless transmission possible. Ultraviolet rays affect a photographic plate and cause it to darken rapidly. The effect that different ether waves produce seems to depend upon their length.

Waves of a certain length affect the *optic* nerve and are called *light* waves. Just as our ears are sensitive to air waves of certain lengths, so our eyes are sensitive to ether waves of certain lengths. Heat waves and radio waves are longer than light waves. Some waves that affect a photographic plate and do chemical work are much shorter.

**401. There are several theories of light.** As early as 1678, Huygens proposed his *wave theory of light* and suggested that light waves are ether waves. The theory met with much opposition and was not generally accepted before the beginning of the nineteenth century. The theory was opposed strongly by Sir Isaac Newton, who favored the *corpuscular theory*. According to the corpuscular theory, or the emission theory, streams of extremely small particles or corpuscles are emitted by *luminous* bodies. Such corpuscles produce the sensation of light when they enter the eye and stimulate the optic nerve. Newton's influence upon scientific thought was great enough to delay the acceptance of the wave theory for about one hundred years.

When Huygens *assumed* the existence of the *ether* as a medium through which light waves are transmitted, men of the eighteenth century found it difficult to accept his theory. It is difficult to try to picture a medium which we cannot see, feel, smell, or taste. We find it hard to imagine a weightless fluid so subtle that it slides in between the molecules and pervades all space, even that of the best vacuum.

---

### Vocabulary

**Luminous**, emitting light.

**Illuminated**, shining because of ability to reflect light received from outside sources.

**Incandescent**, glowing because of being heated to luminosity.

**Photometer** (*phos*, light; *meter*, measure), an instrument used to measure candle power.

**Corpuscle**, a tiny particle.

**Translucent**, transmitting some light.

**Octagonal**, eight-sided.

**Umbra**, a shadow.

**Penumbra**, a partial shadow.

**Photon**, a tiny packet or quantum of light energy.

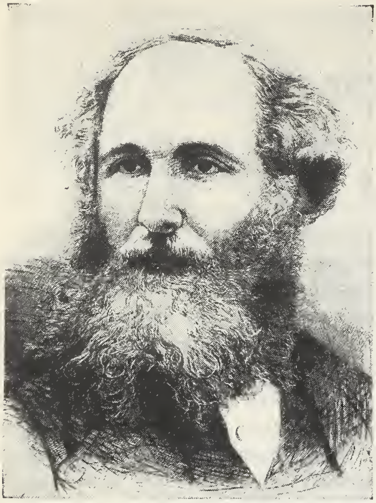


FIG. 426. James Clerk-Maxwell (1831–1879) was a Scotch physicist. In 1873 he published a treatise on "Electricity and Magnetism." He believed that light waves are electromagnetic in their nature. His belief is confirmed by the discovery of the Hertzian waves.

The theory has been accepted because it is difficult to explain some of the phenomena of light by the corpuscular theory.

In 1864, James Clerk-Maxwell, one of the greatest of modern physicists, suggested that light has its origin in ether waves set up by electrical disturbances. His *electromagnetic theory* of light has been commonly accepted, especially since the experiments of Heinrich Hertz seem to confirm Maxwell's suggestion. It is possible, then, that light waves are ether waves which have their origin in the vibrations of electrically charged particles which compose the atoms themselves. (See Fig. 426.)

★Still more recently the *quantum theory of light* has been proposed. Max Planck of Berlin suggested in 1900 that light is transmitted in small bundles or packets of energy called *photons*, or *quanta of light*. Einstein's experiments confirm this theory, and his theory of *relativity* has made many scientists skeptical of the existence of the ether. The beginner in physics will find the wave theory much simpler in his study of light, but he needs to keep in mind that scientists must admit that there is still much to be learned concerning the nature of light. To explain all the various phenomena of light it seems to be necessary to use both the quantum theory and the wave theory.

**402. How do light waves differ from sound waves?** In several ways light waves differ from sound waves:

1. Light waves travel through a vacuum, while sound waves do not. Hence, light waves are ether waves, but sound waves must be transmitted by ordinary matter.

2. Light waves are transverse, while sound waves are longitudinal.

3. Sound waves vary in length from about 1 cm. to nearly 21 meters, while light waves range from 0.000039 cm. to only 0.000081 cm. in length.

4. Light waves travel in straight lines, but sound waves bend around corners readily. We can hear a person who stands around the corner from us, but we cannot see him.

5. Light travels so rapidly that it is considered instantaneous for short distances. The speed of sound is very slow compared to that of light. In one second light travels a distance equal to more than seven times around the earth at the equator.

**403. What are the sources of light?** 1. *Natural.* Nearly all the *natural* light that we receive comes from the sun, which is the center of our solar system.

The distant stars furnish us with some light. Some of the stars are larger than our sun and really give off more light, but they are so far away that we receive only a tiny fraction of the light that they emit. The light we get from the moon is really sunlight reflected to us from the surface of the moon, which acts like a large mirror in its ability to reflect light.

Dr. Michelson, formerly of the University of Chicago, devised a method of measuring the diameters of some of the stars. He found, for example, that Betelgeuse, a bright star in the well-known constellation Orion, has a diameter much greater than that of our sun. The diameter of the sun is about 866,000 miles, but Betelgeuse has a diameter of about 235,000,000 miles. If this super-giant star were placed at the position the sun now occupies, its outer edge would extend out beyond the earth's orbit nearly as far as the orbit of the planet Mars. (See Fig. 427.)

*Science Service*

FIG. 427. Albert Michelson (1852–1931), a physicist at the University of Chicago, devised the mile-long vacuum tube for measuring the velocity of light. He invented the interferometer and was awarded the Nobel Prize in Physics in 1907. He measured the diameter of the star Betelgeuse, which has a diameter much greater than that of the earth's orbit.

2. *Artificial.* There are several ways of producing *artificial* light. Friction may be used to heat objects until they glow. When gas, oil, or other fuel burns, light is produced. Electricity is used to heat tungsten wires to *incandescence,* or until they glow. Sometimes burning fuel is used to heat objects to incandescence.

**404. What is the difference between luminous and illuminated objects?** When a platinum wire is heated, the ether waves that are set up become shorter and shorter as the temperature rises. The wire soon begins to glow, or it becomes incandescent. It is a *luminous* body, visible on account of its own light. An object that gives off light on account of the energy of its own oscillatory particles is said to be luminous. The stars are luminous and emit light. Just as sound and heat are reflected, so light waves may be turned back from the surfaces of bodies. Mirrors reflect light that is received from some other source. A body that merely reflects light which it has received is an *illuminated body.* The moon is an excellent example. Like a huge mirror, it reflects light which it receives from the sun. Some of the planets may be hot enough to be luminous, but most of them are illuminated bodies, reflecting light received from other sources.

**405. What do we mean by reflection, absorption, and transmission of light?** What happens when light waves fall upon the glass of our windows or upon the surface of a body of water? Part of the light is reflected from the glass or the water. Part of it travels through the medium, or is transmitted by it. Still another part of the light is absorbed by the medium itself. It is of interest to inquire more carefully concerning the three different ways in which light that is incident upon various bodies is affected:

1. *Reflection.* Smooth water has been used as a reflector of light from the earliest times. It makes a fairly good mirror. The panes of glass from the window of a distant house reflect light to us. If the glass is removed, we see what appears to be a dark opening. Highly polished metals make good reflectors of light. The planet Venus appears very bright. It is estimated that the surface of Venus reflects about 50% of the light that it receives, while the surface of the planet Mars reflects less than 25% of the light that is incident upon it.

2. *Absorption.* Dark-colored objects are good absorbers of light. Black objects absorb all the light that falls upon them. When the *vertical* rays of the sun are incident upon a body of water, most of their light is either absorbed or transmitted. More of the rays are reflected when they strike the water at an oblique angle. You can probably look at the image of the sun in the water without discomfort when the sun is directly overhead, but your eyes are dazzled by the reflected rays from the setting sun.

3. *Transmission.* Air, glass, and water transmit light readily. They are said to be *transparent.* So much light is transmitted by transparent bodies that it is easy to distinguish objects through them. Formerly, oiled paper was used in windows as a substitute for glass. Light passes through such paper, but the amount transmitted is too small to enable one to *distinguish objects* through it. Such paper is said to be *translucent.* Frosted electric bulbs and some lamp shades are also examples of translucent substances. They transmit some light, but so much of the light is scattered or diffused that objects seen through them cannot be identified. *Opaque* substances do not transmit light at all. Hence we cannot see through them. No substance is perfectly transparent, since the clearest air or the clearest water absorbs some light rays. On the other hand, no substance is perfectly opaque. We think of gold as being opaque, but when gold is beaten into extremely thin sheets, it transmits some light. A sheet of steel an inch thick is opaque to light, but it is possible to grind steel sheets so thin that they transmit intense light. With our eyelids closed, we can tell when a light has been turned on in a darkened room.

**406. What are rays, beams, and pencils of light?** From a luminous point, light waves travel outward in all directions. If the medium is of the same nature throughout, the light travels in straight lines. When one aims a rifle he makes use of this fact, since the light from the object at which he aims is reflected along the two sights of the rifle. A single line of light coming from a luminous point is called a *ray.* Several parallel rays form a *beam* of light. The rays coming from the sun are so nearly parallel that we may consider them as beams. When several rays of light come from a point they form what is called a *diverging pencil.* Rays from an auto-

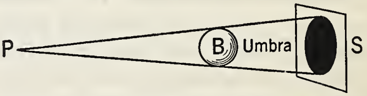


FIG. 428. The umbra is the darkest part of a shadow.

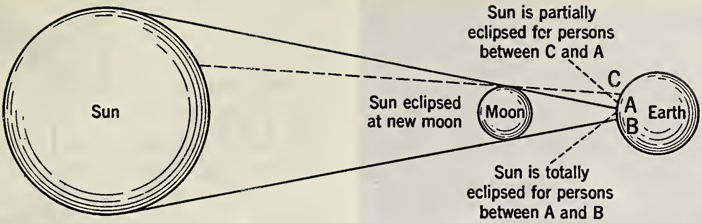

Sun is partially eclipsed for persons between C and A
C
Sun
Sun eclipsed at new moon
Moon
A
Earth
B
Sun is totally eclipsed for persons between A and B

FIG. 429. The sun may be eclipsed when the moon comes directly between the earth and the sun.

mobile headlight are somewhat diverging. Several rays of light proceeding toward a point form a *converging pencil.* When the sun's rays pass through a burning glass, they are bent as they pass through the glass. They converge to a point called a *focus.*

**407. What causes shadows?** Since an opaque object absorbs light, the space behind it is in darkness. Any space from which the light is excluded by an opaque object is called a *shadow.* When the source of light is a point, as in Fig. 428, all the rays will be cut off from the dark part of the screen *S* by an opaque ball *B*. If the light comes from a spherical object, the shadow will vary in intensity. (See Fig. 430.) The part from which all the rays of light are excluded, included in the cone *DCF*, is called the *umbra.* The lighter parts of the shadow, *CFy* and *CDx*, are called the *penumbra.* The luminous ball *S* is not entirely hidden from an observer between *x* and *C*, but part of its rays are cut off.

**408. How are eclipses caused?** When Alexander the Great asked Diogenes how he could serve him, the reply of Diogenes was: "You can stand out of my sunlight." Diogenes objected to being eclipsed by King Alexander. When the moon revolves around the earth, it may come almost directly between the earth and the sun. This can happen only at *new* moon. Then it cuts off the sun's rays and we have an eclipse of the sun. Certain portions of the earth's surface fall within the shadow of the moon. When the moon is at the position shown in Fig. 429, the sun will be totally eclipsed for an observer at any place on the earth between *A* and *B*.

In its revolution around the earth, the moon may pass through the earth's

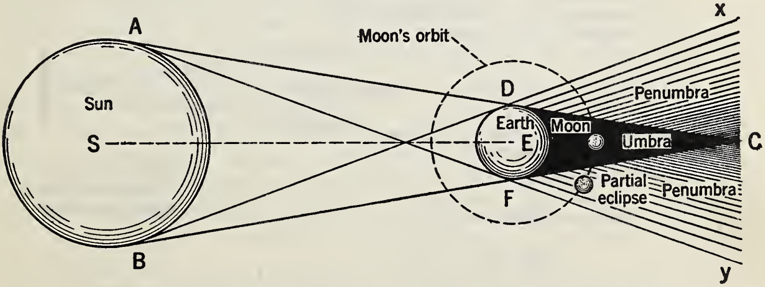

A
Sun
S
B
Moon's orbit
D
Earth
E
F
Moon
Umbra
Penumbra
Partial eclipse
Penumbra
x
C
y

FIG. 430. The moon is eclipsed when it passes through the earth's shadow.

*Courtesy of the American Museum of Natural History*

FIG. 431. Photograph of total eclipse of the sun.

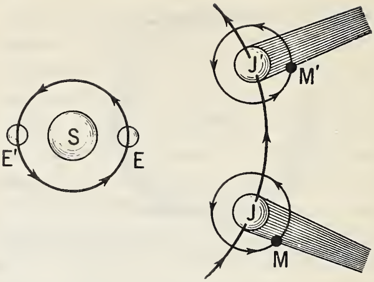


FIG. 432. A diagram to show Roemer's method of calculating the velocity of light.

shadow. Then we have an eclipse of the moon, which can happen only at *full* moon. (See Fig. 430.) At one position we see the moon passing from the earth's penumbra into its umbra. Then it passes on through the umbra and the other portion of the penumbra, and the eclipse ends. Since the moon does not shine of its own light, it appears dark when the sun's rays are cut off by the earth. (See Fig. 431.)

**409. How fast does light travel?** Light travels so fast that it appears to be instantaneous. In fact, Galileo concluded that no time at all was required for light to travel from one place to another. His conclusion was accepted until the year 1675, when Roemer, a Danish astronomer, found a method for measuring the velocity of light. He watched the time of the eclipses of one of Jupiter's satellites or moons, first when the earth was on the side of the sun nearest to Jupiter and six months later when the earth was on the opposite side of the sun. From Fig. 432,

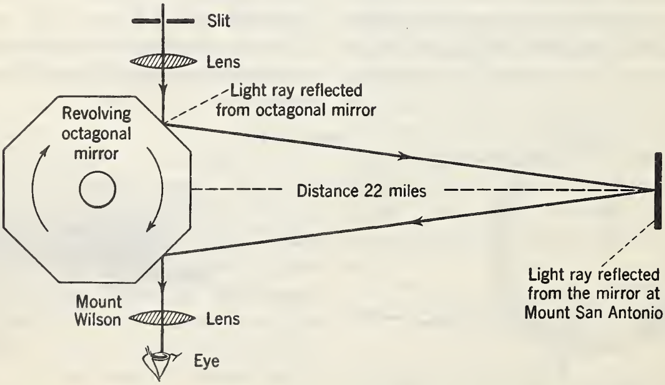

Slit
Lens
Light ray reflected from octagonal mirror
Revolving octagonal mirror
Distance 22 miles
Mount Wilson
Lens
Eye
Light ray reflected from the mirror at Mount San Antonio

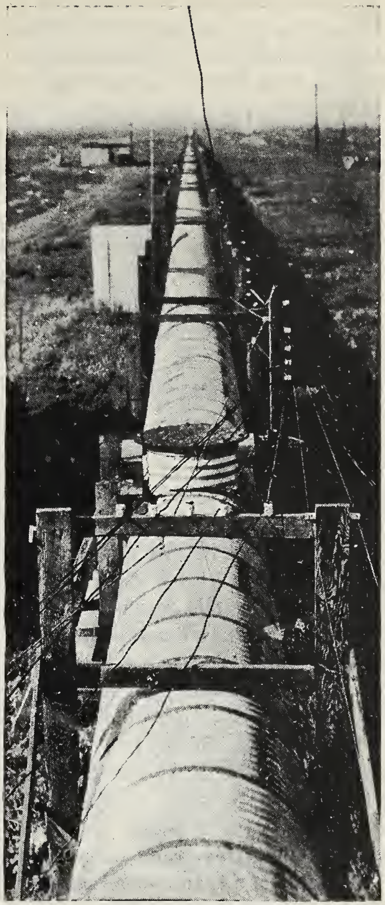
FIG. 433. Octagonal mirror as used to measure light velocity.

we see that the satellite $M$ is just entering the umbra of the planet Jupiter. Roemer observed this eclipse from the earth at the position $E$. Six months later the earth was at $E'$, on the opposite side of the sun from Jupiter, which in the meantime had moved to the position $J'$. From $E'$ Roemer observed the eclipse of the same satellite $M'$. But in this particular case, he found that the eclipse occurred 16 min. and 36 sec. later than the time that it should have occurred from his calculations. He knew that he was 186,000,000 miles farther from Jupiter than before. Hence he concluded that the difference in time must be the time actually required for light to travel across the earth's orbit. If light travels 186,000,000 miles in 996 sec., then the velocity of light must be a little more than 186,000 miles per second.

Other methods for finding the velocity of light have been used. Dr. Michelson, Fig. 427, formerly of the University of Chicago, used two different methods:

1. *Use of octagonal mirror.* An octagonal mirror was set up at the Mt. Wilson observatory in California and concave and plane mirrors at Mt. San Antonio, about 22 miles distant. A ray of light, reflected from one of the octagonal faces of the rotating mirror to the mirrors at Mt. San Antonio, was reflected back again in a parallel line to Mt. Wilson, where it was observed by means of a telescope. A series of flashes were reflected from the rotating mirror every eighth of a rotation. Knowing the distance between the two places, and measuring the time needed for every eighth of a revolution, he could calculate the velocity of light. (See Fig. 433.)

2. *The mile-long tube.* The method



*Courtesy of Mount Wilson Observatory*

FIG. 434. The mile-long vacuum tube used by Michelson to eliminate errors due to haze and variations in air density while measuring the velocity of light. Scientists are always striving for greater accuracy of measurement. Try to imagine the amount of labor involved in constructing such a tube and evacuating it in order to eliminate the slight error that air currents or a slight haze might produce. It does not seem very strange that so careful and painstaking a man should be awarded the Nobel Prize. Edison is said to have made the following remark: "Genius is 95% perspiration and 5% inspiration." No one can be certain about the relative percentages, but there is no doubt that both are necessary for success.

just given is subject to errors due to haze and to varying density of air. For more accurate work, Michelson constructed a *mile-long vacuum tube* in which the light was reflected back and forth ten times. The value he obtained by this method is 186,285 miles per second, which is not believed to be more than one mile in error. (See Fig. 434.)

The velocity of light in water is about $\frac{3}{4}$ as great as in air. In ordinary glass it is about $\frac{2}{3}$ as great. Light travels slightly faster in a vacuum than in air.

## 2. Photometry

**410. What do we mean by intensity and illumination?** In our study of sound we learned that an *intense* sound may not seem very loud to an auditor at a considerable distance from the source. The *intensity* of a light source depends upon the energy produced by the luminous body. It is measured in *candle power*. The brightness of the light which we receive depends not only upon the candle power which the light source gives, or upon its *intensity*, but also upon our *distance* from that source. The amount of light that we receive is measured in *foot-candles*.

Of course, one will get just twice as much light from a 40-candle-power light as he will from a 20-candle-power light, provided that he is the same distance from each one. If we study Fig. 435, we can understand why light appears to grow dimmer as we move farther away from its source.

The light is emitted from a luminous point at *P*, and it spreads out in all directions. Suppose we place the screen *A*, which has an area of just 1 sq. ft., exactly 1 ft. from the light source. *B*, which is four times as large, is placed 2 ft. distant; and *C*, which has nine times the area of screen *A*, is placed 3 ft. away. Both the screens *B* and *C* are completely shaded by the screen *A*. When the screen *A* is removed, then those rays of light which had illumined *A* will fall upon the screen *B*. But *B* has an area of 4 sq. ft., while the area of *A* is only 1 sq. ft. Hence each sq. ft. of surface at *B*, 2 ft. from the light source, can receive only one-fourth as much light as 1 sq. ft. of surface at *A*, only 1 ft. distant. Likewise, *C* is three times as far away as *A*, and the light will be spread over nine times as much area. Thus 1 sq. ft. of surface will receive only one-ninth as much light at *C* as at *A*.

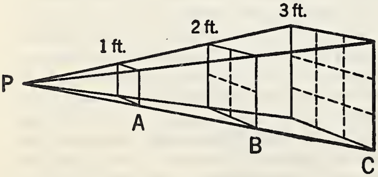


Fig. 435. How increasing the distance affects the amount of illumination a body receives.

These observations, which can be verified by experiment, may be summarized in a general statement known as the LAW OF ILLUMINATION. *The amount of light a body receives is inversely proportional to the square of its distance from the source of light.* A man who is 20 ft. from an arc light will receive only one-fourth as much light as one who is only 10 ft. away.

**411. How is light measured?** From the preceding section, it seems evident

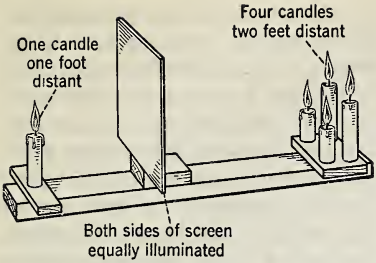

Four candles two feet distant
One candle one foot distant
Both sides of screen equally illuminated

FIG. 436. Amount of illumination is inversely proportional to the square of the distance from light source.

that there must be at least two standards for measuring light: one to measure the intensity of the light at its source, and the other to measure the amount of light which an illuminated body receives. (See Fig. 436.)

*The standard candle* is used to measure the intensity of light. A light of 10 candle power gives out 10 times as much light as a standard candle. The standard formerly used was a sperm candle burning 120 grains of wax per hour. Such a candle has to be kept carefully trimmed to give exactly one candle power of light. At the present time, incandescent electric lights are nearly always used instead of the standard candle, since the amount of light they emit is very constant if the voltage does not vary.

Incandescent lamps used for interior lighting generally range from a few candle power to several hundred candle power. A 40-watt bulb, for example, gives about 32 candle power. A 100-watt bulb gives about 100 candle power. The ordinary arc light gives about 500 candle power. Some very powerful searchlights give several million candle power.

If we observe closely the ordinary tungsten lamp suspended vertically with the shade removed, we notice that the light emitted horizontally is much more intense than that given off vertically. Candle power may refer to horizontal illumination, or to illumination in any direction. The candle power of the arc light as already given is the average of the candle powers in all directions, or its *mean spherical* candle power. The maximum candle power of the arc light is much more than 500. (See Fig. 437.)

The *foot-candle is used to measure illumination.* As the name implies, the foot-candle must depend upon the candle power of the light and the distance. *The foot-candle is the amount of*

| Angle | Candle-power |
|---|---|
| 0 | 142.0 |
| 5 | 148.0 |
| 15 | 161.0 |
| 25 | 178.0 |
| 35 | 183.0 |
| 45 | 181.0 |
| 55 | 165.0 |
| 65 | 108.0 |
| 75 | 44.1 |
| 85 | 5.1 |
| 90 | |

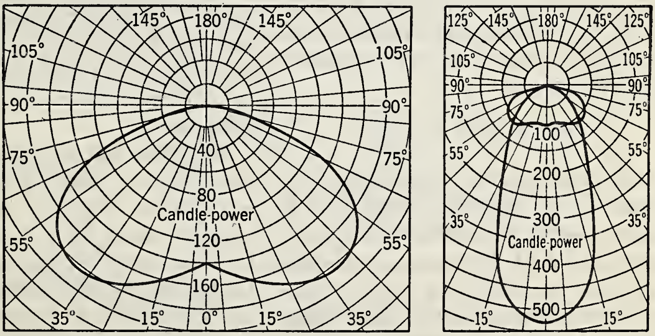
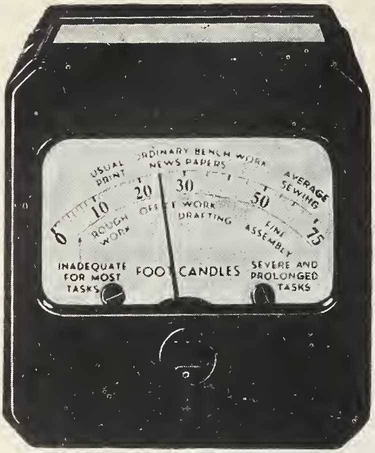


FIG 437. The cut at the left shows illumination in all directions from an unshaded lamp. The cut at the right shows how illumination is directed by a shade.



*Courtesy of Westinghouse*

FIG. 438. Foot-candle meters may be so graduated that they show the amount of light in foot-candles by comparison, or they may be made to read directly. Out-of-door photographers make use of such meters to measure the brightness of light.

*light one would receive from a standard candle at a distance of one foot.* A person seated 1 ft. from a 20-C.P. lamp receives 20 foot-candles of light. (See Fig. 438.) If he sits at a distance of 2 ft. from such a lamp, he receives only 5 foot-candles.

$20 \div (2)^2 = 5$. (LAW OF ILLUMINATION.)

The number of foot-candles may be found by dividing the candle power of the light by the square of the distance measured in feet.

$$\text{Foot-candles} = \frac{\text{C.P.}}{d^2}.$$

★In illuminating engineering, the *lumen* is an important unit that is much used. It denotes the quantity or amount of light. If we place a standard candle at the center of a sphere of one-foot radius, the amount of light falling upon one square foot of the inner surface of the sphere is one lumen. Or, if we cut in the sphere an opening whose area is exactly one square foot, the amount of light which escapes from the opening is one lumen. If we make the size of the opening two square feet, then two lumens of light escape. Since the area of such a sphere is 12.57 sq. ft., then the total amount of light emitted by a candle is 12.57 lumens. Of course, if we have a 2-C.P. light at the center of a sphere of one-foot radius, the amount of light falling upon every square foot of area is two lumens. Hence,

*lumens = foot-candles × area in sq. ft.*

**412. How much light do we need?** The number of foot-candles needed varies with the kind of work one is doing. Too much light is quite as injurious to the eyes as too small an amount. Engineers seem to be gradually increasing their figures for the amount of light needed. They now suggest 8 to 10 foot-candles for reading ordinary print. For reading fine print, 15 foot-candles may be needed. One who uses fine thread for sewing, especially with black goods, requires at least 15 to 20 foot-candles.

Formerly, many factories were poorly lighted. Now, engineers make a study of the lighting problems, because sufficient light speeds up the work and fewer accidents result. Efforts are made to eliminate glare and to prevent shadows.

**413. How can we economize?** Suppose that we need 8 foot-candles for our reading. We may use a 40-watt lamp of about 32 C.P. and sit 2 ft. from the lamp. We may use a 72 C.P. lamp and have it 3 ft. away, or we may use a 25-watt bulb furnishing 20 C.P. and hold our book about 1.5 ft. from the bulb. In the first case, it costs us

60% more for electric current than in the last case, and in the second case more than 200% more. Evidently, if we wish to be economical, we shall arrange to have our lights near our work.

**414. How is candle power measured?** We measure the candle power of any light source by comparing the intensity of its light with that of some standard candle or lamp. The instrument used is called a *photometer*. Several types are in use:

1. *Bunsen photometer*. In this photometer, sometimes called the grease-spot photometer, a piece of paper, in the center of which there is a grease spot, is placed on a meter stick between the *standard* candle and the lamp of *unknown candle power*. Then it is moved back and forth along the meter stick until it is equally illuminated on both sides. When the paper is equally illuminated on both sides, the grease spot practically disappears. (See Fig. 439.) If we hold such a piece of paper toward the window, the grease spot will appear lighter than the rest of the paper because it transmits light better. It is a poorer reflector of light than the paper, and it appears darker than the paper when held away from the window so that we see it by reflected light. When the paper screen is properly adjusted, we measure the distance from the standard lamp to the grease-spot screen, and the distance from the lamp of unknown candle power to the screen. *The candle powers of the two light sources are directly proportional to the squares of their distances from the screen.* This is the LAW OF INTENSITY of light. It must not be confused with the LAW OF ILLUMINATION of light. The former depends upon the amount of energy of the luminous body, and the latter upon the amount of that energy which the illuminated body receives.

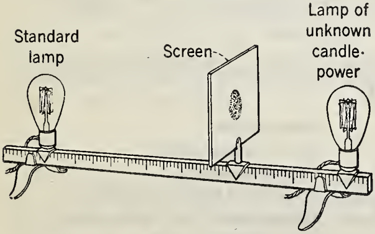


FIG. 439. The Bunsen, or grease-spot, photometer.

*Courtesy of Westinghouse*

FIG. 440. In the spherical photometer the light is placed at the center of a large sphere. The amount of illumination is measured by means of a photo-electric cell.

Suppose that we use a 20-C.P. lamp as our standard. The screen is equally illuminated when it is 20 cm. from the standard and 80 cm. from the lamp of unknown candle power. Evidently the unknown lamp must have the greater intensity, since it supplies as much light at a distance of 80 cm. as the standard does at a distance of 20 cm. It must be $\frac{(80)^2}{(20)^2}$, or 16, times as intense. Hence, its candle power equals 16 × 20, or 320 C.P.

2. *Joly photometer*. This is a simple photometer suitable for student use.

It consists of two blocks of paraffin separated by tin foil. The light on either side is transmitted by the paraffin, but not by the tin foil. The observer can tell when the illumination on both sides is equal by looking at the edges of the paraffin blocks and judging when both are illuminated to the same depth equally. The distances are then measured, and the calculations made in exactly the same manner as with the Bunsen photometer.

3. *Spherical photometer.* This accurate photometer is much used commercially. The lamp is placed in the center of a large sphere which is painted white on the inside. The intensity of the light transmitted through a window is measured by means of a photo-electric cell. The more intense the light, the stronger the current which it produces in the photo-electric cell. This cell is discussed more fully in a later chapter. (See Fig. 440.)

## Summary

Like heat, light is also a form of radiant energy. It travels in straight lines at a velocity of about 186,000 miles per second.

An object may reflect, absorb, or transmit the light waves which it receives. A substance that transmits light readily is said to be transparent. If a substance does not transmit light at all, it is said to be opaque.

That part of a shadow formed by the exclusion of all the light is called the umbra; that portion from which only a part of the light is excluded is called the penumbra.

An eclipse of the sun is caused when the shadow of the moon falls upon the earth. An eclipse of the moon occurs when the moon passes through the earth's shadow.

The amount of light which a body receives is directly proportional to the intensity of the luminous object and inversely proportional to the square of the distance between the light source and the illuminated body.

Photometry deals with the measurement of the intensity of light. Intensity is rated in candle power. The amount of illumination received is measured in foot-candles. The quantity of light emitted is measured in lumens.

Several types of photometer are in use: The Bunsen, Joly, and spherical are the most common.

*How many of the following terms and phrases can you define or explain? (Can you explain them all from memory?)*

Nature of light
Sources of light
Michelson
Theories pertaining to light
Light waves compared to sound waves
Reflection of light
Shadows
Eclipses
Photometry
Velocity of light
Intensity of light
Candle power
Octagonal mirror
Foot-candles
Law of illumination
Law of intensity
Amount of light one needs
Measurement of candle power
The mile-long tube
Bunsen photometer

## QUESTIONS

1. Is it possible to have an eclipse of the moon at new moon? Explain.

2. Can there be an eclipse of the sun at full moon? Explain.

3. Do light and heat travel at the same velocity? Give a reason for your answer.

4. In describing eclipses, an almanac speaks of the moon as entering the earth's penumbra and then its umbra. What do the expressions mean?

5. Do you think that you could hit a target with a rifle if light did not travel in straight lines? Explain.

6. If a substance were perfectly transparent, would it be visible? Explain.

7. What is the advantage of having a lamp fixture at the center of a room near the ceiling? What are the disadvantages?

8. How do light waves differ from sound waves?

9. How are shadows caused?

10. Upon what two factors does the amount of light that one receives depend? How can each one be varied?

11. The moon is about 240,000 miles from the earth. The diameters of the sun and moon are respectively about 866,000 miles and 2000 miles. Show by a diagram why the sun can never eclipse more than a small portion of the earth's surface at any one time.

12. The planet Mercury is about one-third as far from the sun as the earth. How does the amount of light received there compare with the amount which we receive?

## PROBLEMS

### Group A

1. Using the speed of light in air as 186,000 miles per second, calculate the speed of light in water.

2. Calculate the speed of light in ordinary glass.

3. A stick 4 ft. long casts a shadow 6 ft. long; how high is a tree that casts a shadow 120 ft. long?

4. A man is seated 2 ft. from a lamp of 20 C.P. How many foot-candles of light does he receive?

5. If a man is seated 3 ft. from a lamp of 40 C.P., how many foot-candles of light does he receive?

6. Compare the costs of operating the two lamps of Problems 4 and 5. For economy, what would you suggest to the man of Problem 5?

7. What is the approximate candle power of the bulb in your reading lamp? Measure its distance from your book as you ordinarily sit to read. How many foot-candles are you getting?

8. A reads from a 20-C.P. lamp 2 ft. distant; B reads from a 100-C.P. lamp 5 ft. away. How many foot-candles does each one receive? Compare the cost of operating these lamps.

9. The screen of a photometer is found to be equally illuminated on both sides when a 20-C.P. lamp is 10 cm. away on one side, and an arc lamp is 60 cm. from the other side. What is the candle power of the arc lamp?

10. A tree 80 ft. high is 240 ft. distant. How far from the eye must a 6-inch pencil be held to appear the same height as the tree?

11. What candle-power lamp will yield 10 foot-candles of light at a distance of 2.5 feet?

12. For a certain piece of work a person needs 8 foot-candles of light. He has a 60-C.P. lamp. How far away must the lamp be placed to give the desired amount of light?

### Group B

13. At one end of a meter stick a standard candle is placed. At the other end of the stick there is a lamp of unknown candle power. A screen is equally illuminated on both sides when it is 20 cm. from the standard candle. Calculate the candle power of the lamp.

14. A reading room has a 12-ft. ceiling. Which is better, to light the room with 4 arc lamps of 500 C.P. each, suspended 2 ft.

from the ceiling, or to use 16 incandescent lamps of 100 C.P. each, suspended 5.5 ft. from the ceiling? (Assume that the reading tables are 30 inches high.) Calculate the maximum number of foot-candles a reader would receive in each case.

15. Light that left the star Arcturus in 1893 was used to operate a photo-electric cell and turn on the lights for the Century of Progress in 1933. How far distant is the star Arcturus?

16. At one end of a meter stick is a 32-C.P. lamp; at the other end there is a 9-C.P. lamp. Where must a screen be placed between the two to be equally illuminated on both sides? (*Hint.* Let $x$ equal one distance, and $100 - x$ the other.) Form an equation.

17. The planet Mars is about 140,000,000 miles from the sun. The earth is about 92,500,000 miles. Compare the relative amounts of heat and light that each planet receives from the sun.

18. The radius of the sun is 433,000 mi.; the radius of the earth is 4000 mi.; the distance between the sun and the earth is 92,500,000 miles. In Fig. 430, $AS$ represents the radius of the sun, $ED$ the radius of the earth, and $SE$ the distance between the sun and the earth. Calculate $EC$, the length of the earth's shadow. (*Hint.* Note that $ASC$ and $DEC$ are similar triangles. $SC$ is equal to 92,500,000 miles plus $x$ miles.)

# Light — Reflection

**415. What factors govern the reflection of light?** The amount of light an object reflects depends upon the *nature of the material*, the *polish of the surface*, and the *angle at which the light strikes the surface.* Mirrors are highly polished to make them better reflectors. The glare of the rising or setting sun upon the water teaches us that more light is reflected when the rays are incident upon the surface at an oblique angle. At noonday it is not difficult to look at the image of the sun in the water, because perpendicular rays are more completely absorbed.

**416. What is the law of reflection?** The reflection of light is not unlike that of sound, or the rebound of a ball. Suppose we let *MN* of Fig. 441 represent a reflecting surface. *AD* is a ray of light *incident* upon the reflector at *D;* and *DB* is the path of the reflected ray. *CD* is a perpendicular to the reflecting surface which may be plane or curved; in physics it is generally called the *normal.* The angle *ADC* is called the *angle of incidence;* the angle *BDC* is the *angle of reflection.*

By actual experiment it may be shown that *the angle of reflection is equal to the angle of incidence.* This statement, which is true of all cases, is known as the LAW OF THE REFLECTION OF LIGHT. If we increase the angle of incidence, the angle of reflection is correspondingly increased. If we stand directly in front of a mirror we can see our own image, because a ray of light incident upon the mirror along the normal is reflected back upon itself. The angle of incidence is zero and the angle of reflection must also be zero. The incident ray, the normal, and the reflected ray must always lie in the same plane.

**417. What is regular reflection?** Every schoolboy has used a piece of mirror to reflect the sunlight into the eyes of some one across the room. Regular reflection from such surfaces produces so much glare that it is difficult to see clearly. The rays from the sun are nearly parallel, and have the

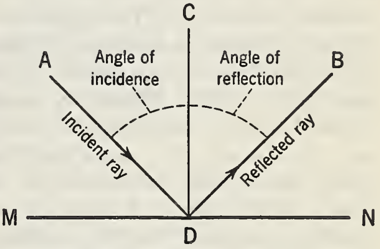


FIG. 441. Angle of reflection equals the angle of incidence.

---

## Vocabulary

| | |
|---|---|
| ABERRATION | wandering, or non-focusing. |
| APERTURE | an opening. |
| DIFFUSION | as applied to light, a scattering of light rays. |
| VIRTUAL | apparent or formed by imaginary rays. |
| IMAGE | a picture or optical counterpart of an object. |
| FOCUS | a point at which rays meet or appear to meet. |
| NORMAL | a line which is drawn perpendicular to a surface. |

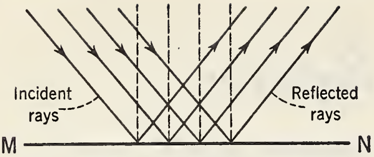


FIG. 442. Regular reflection of light.

same angle of incidence; hence they are nearly parallel as they are reflected from the mirror. Fig. 442 shows us how a beam of light is reflected from a polished, plane surface. One finds it hard to read from a glazed paper in strong sunlight. The fact that one may walk into large mirrors or plate glass is evidence that neither perfect reflectors nor transparent objects are easily visible.

**418. What is diffused reflection?** If we refer to Fig. 443, it will be easy to understand what happens when a beam of light is incident upon an *irregular* surface. Of course the law of reflection holds true for each particular ray of light, but the normals to the surface are not parallel, and the light is scattered in all directions. The importance of such *diffusion*, or scattering of light can hardly be over-estimated. If the sun's rays were not diffused by rough surfaces and by dust particles in the air, the corners of a room and the space under shade trees would be in almost total darkness. In front of the windows the glare would be dazzling.

**419. How is diffusion of light promoted?** To avoid glare, it is necessary at times to promote diffusion of light by *reflection* or *transmission*. Let us mention briefly some of the methods used in each case.

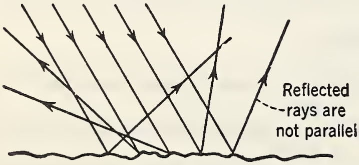
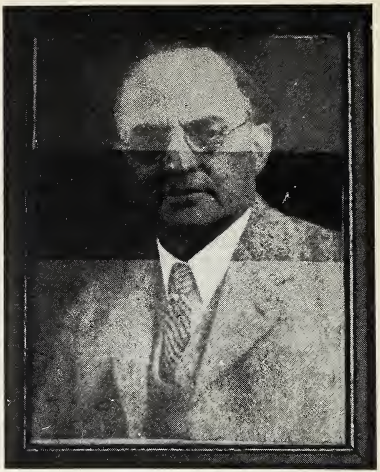


FIG. 443. Light is diffused by irregular reflection.



*Courtesy of the General Electric Company*

FIG. 444. Nearly all the light passes through the film-covered glass. Untreated glass shows extensive glare.

1. *By reflection.* Our newspapers are printed on unglazed paper. They are easier to read because the rough surface diffuses the light. In order to have the illustrations appear more clearly, books are often printed on *semi*-gloss paper. The *semi*-gloss paper is a compromise, since half-tones should be printed on *full*-gloss paper to be effective, but the printed matter on the same page would be difficult to read. Wall papers for living rooms and bedrooms are not usually glazed. Their roughened surfaces promote diffusion. Glazed wall papers are popular for bath rooms and kitchens because they are washable and easily kept clean. The furniture and woodwork in our homes are often left with a dull finish to prevent glare from regular reflec-

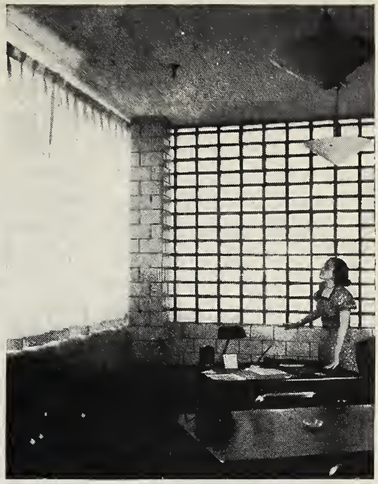
tion. The egg-shell finish is popular, but not so easily kept clean as a more glossy finish. Dr. Katherine Blodgett has developed a process of coating glass with very thin layers of chemical films to prevent glare. (See Fig. 444.)

2. *By transmission.* Nearly all electric bulbs are now frosted on the inside to promote diffusion and prevent glare. Parchment shades soften the light by promoting diffusion. Prism glass and various other types of roughened glass are frequently used in windows to help prevent glare. (See Fig. 445.) Opalescent lamp shades and globes accomplish the same purpose, and manufacturers are still attempting to make lenses which, by means of better diffusion, will prevent glare from automobile headlights.

**420. What is a mirror?** Any highly polished surface which can be used to form images by the regular reflection of light is a mirror. For ordinary looking glasses, or mirrors, *plane* pieces of ordinary glass or plate glass are *silvered* on one surface so that a large quantity of light will be reflected. Even the best mirrors do not reflect all the light which they receive, and we never see ourselves more than 70% as bad or as good as others see us.

For special purposes, *curved* mirrors are used. Such curved surfaces may form part of a sphere, a cone, or a cylinder. Curved mirrors are either *concave* or *convex.* When the outside surface of a sphere is the reflecting surface, the mirror is convex; the inside of a hollow sphere forms a concave mirror. Peculiarly curved mirrors are sometimes used in amusement parks to produce grotesque images.

**421. There are two kinds of images.** Rays of light are sometimes reflected from a curved mirror in such a manner that they meet in front of the mirror to form an image of the object from which the light comes. Such a picture or visual counterpart of the object may be thrown upon a screen. An image of this kind, which is formed by actual rays of light, is called a *real image. Real images are always inverted, but they may be either larger or smaller than the object.*



*Courtesy of the Owens-Illinois Glass Company*

Fig. 445. Buildings of the future may have glass walls and no windows. Light is diffused through the walls.

When a person looks at his own image in a plane mirror, the rays of light *appear to come* from behind the mirror. Of course, the real rays of light are reflected from the surface of the mirror, but they *seem to meet* behind the mirror to form the image. An image of this kind is called a *virtual image.* Of course, such an image cannot be thrown upon a screen. *Virtual images are always erect.* They, too, may be *enlarged or reduced in size.* In a later chapter we shall see how lenses, too, can be used to form images.

**422. How do small openings form images?** If we punch a pinhole in a window shade in a darkened room on the sunny side of the house, a small image of the sun may be thrown upon a piece of white paper held a foot or more from the opening. In a dark room, it is possible to form an excellent image of a candle flame upon a white screen by letting the rays from the candle pass through a small aperture. (See Fig. 446.) Since light travels in straight lines, a ray of light from $A$, the tip of the candle, will pass through the opening to form an image of the tip of the flame at $A'$. From $D$ a ray of light will fall upon the screen at $D'$. Rays from $B$ form an image at $B'$. If the opening is very small, the image will be sharp and well-defined, but not very bright. Increasing the size of the opening makes the image brighter, but it becomes less distinct. The pinhole camera is an application of this method of forming images. Fairly good pictures may be taken with such a camera.

We notice that the triangles $ABC$ and $A'B'C$ of Fig. 446 are similar. Therefore, $AB : A'B' = BC : B'C$. But, $AB$ is equal to half the size of the object, and $A'B'$ is equal to half the size of the image. $BC$ equals the distance of the object from the aperture, and $B'C$ is equal to the distance of the image from the aperture. Therefore, we conclude that the *relative sizes of the object and image are proportional to their relative distances from the opening.*

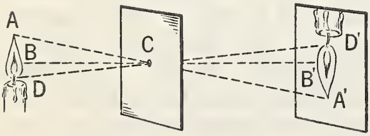


Fig. 446. Tiny openings may be used to form images.

Increasing the distance of the object reduces the size of the image, but moving the screen farther from the opening increases the size of the image.

Problem. An object 6 ft. tall is 8 ft. from an aperture which forms an image on a screen placed 4 in. from the opening. Find the size of the image.

*Solution.* Size of object : size of image = object distance : image distance. Substituting, 72 in. : $x$ in. = 96 in. : 4 in. Whence, $x$ equals 3 in., the size of the image.

**423. What kind of images are formed by plane mirrors?** When one looks at his image in a plane mirror, he finds that his image is neither enlarged nor reduced; it is erect; it is virtual, since the rays seem to come from behind the mirror; it is as far behind the mirror as the observer is in front. Since the image is formed on the *normal* produced, it will be reversed; the right side will appear as the left side of the image, and vice versa.

By laboratory experiment it is possible to construct the image of an object as formed by a plane mirror. Let us use for the object a triangle, $ABC$, drawn upon a sheet of paper. (See Fig. 447.) The mirror is placed on the line $MN$. A pin is then placed at the vertex

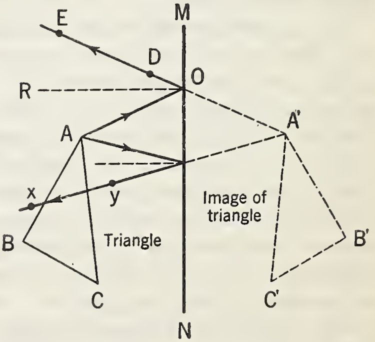


Fig. 447. How images are formed by plane mirrors.

$A$ of the triangle. By looking at the image of this pin in the mirror, it will be found possible to arrange two pins, $E$ and $D$, in line with the image of the pin at $A$ as seen in the mirror. Since light travels in straight lines, the image of the pin will be on the line $ED$ produced behind the mirror. In the same manner we may set two pins, $x$ and $y$, in line with the image of the pin at $A$. The image is also on this line produced. Since $A'$, the point of intersection of the two sight lines, is the only point common to both lines, the image of $A$ must be at the point $A$ . By the same method, it is possible to locate the image of the point $B$ at $B'$, and of the point $C$ at $C'$. In all these cases *the image is found to be as far behind the mirror as the object is in front.* By joining the points, we prove that *the image is the same size as the object.*

This method of constructing images also verifies the law of reflection of light. As we look along $ED$, we see the ray of light coming from $A$. It is incident upon the mirror along the line $AO$; from the point $O$ it is reflected along $ED$. When we erect a perpendicular or normal to the mirror at $O$, we bisect the angle $AOE$. The angle $EOR$, which is the angle of reflection, is equal to the angle of incidence $AOR$.

**424. What are some uses of plane mirrors?** By Ovid we are told that Narcissus became so infatuated with his image in the water that he was changed into the flower which bears that name. From the very earliest times mirrors have been used as looking glasses. We also use them in our houses for their decorative effect. They are frequently used by the army signal corps for flashing signals. Nearly all closed automobiles are fitted with plane mirrors to enable the driver to see cars behind him.

**★425. What is multiple reflection?** Just as sound waves bound and rebound between parallel cliffs or walls to produce echoes and re-echoes, so light waves are reflected back and forth between parallel mirrors or mirrors set at an acute angle, forming multiple images. The image formed in one mirror acts as the object which forms an image in the second mirror. Another image of this image may then be formed. Since some light is absorbed each time, each succeeding image is fainter than the one just preceding. The kaleidoscope is an example of multiple reflection. Three mirrors set at angles of 60° form multiple images of vari-colored pieces of glass. Some beautiful designs are produced in this manner.

A thick plate-glass mirror also shows multiple reflection because both surfaces are reflectors. Fig. 448 shows how the ray of light $AB$ is partially reflected to $C$; a part passes through the glass to $D$, the back of the mirror, whence it is again reflected. The path the ray may take is shown by the arrowheads. When it reaches the front surface, it is divided; a part enters the air, and a part is reflected to the back surface again. A gas-jet or electric light as viewed in a plate-glass mirror shows such a series of images.

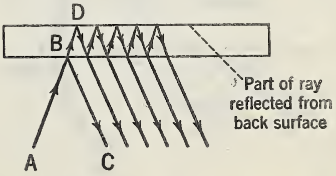


Fig. 448. Light is reflected from both the front and rear surfaces of a mirror.

**426. Terms used with curved mirrors.** Before one can understand how images are formed by curved mirrors, it will be necessary to define several terms which are used. Let us assume that the mirror which we are using is part of the surface of a sphere. We represent the mirror by the arc of a circle. By the use of Fig. 449 these definitions may be clarified.

1. The *center of curvature, C,* is the center of the sphere of which the mirror forms a part.
2. The *aperture* is the angular portion, *MCN,* of the sphere that is included by the mirror. Generally only a few degrees of the total surface are used as the reflecting surface.
3. The *vertex, V,* is the center of the mirror itself.
4. The *principal axis* is the line *PV* drawn through the center of curvature and the vertex.
5. Any other line drawn through the center of curvature, *SS′* for example, is called a *secondary axis.*
6. The *normal* to the surface of a concave mirror is the radius drawn from the point of incidence, since the radius is perpendicular to a tangent to the surface. In a convex mirror, the normal is the radius produced.

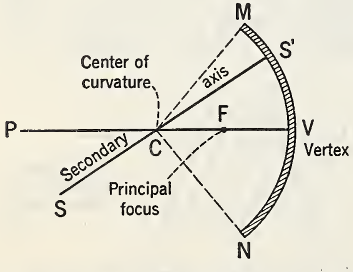


Fig. 449. Definitions pertaining to curved mirrors.

**427. How are light waves focused?** Let us draw two lines *AD* and *BE* to represent rays of light parallel to the principal axis, both incident upon a concave mirror as shown in Fig. 450. From the points of incidence we draw the normals *CD* and *CE*. By construction we make the angles of reflection *CDF* and *CEF* exactly equal to the angles of incidence *ADC* and *BEC*, respectively. Thus we find that these parallel rays are reflected from the mirror to meet at the point *F*. Such a point where rays meet is called a *focus.* With a convex mirror, the reflected rays are divergent, but they seem to meet at a point back of the mirror. Such a point is a *virtual focus.* If the aperture of the mirror is small, rays of light parallel to the principal axis will meet or appear to meet at the *principal focus,* which is a point *midway between the center of curvature and the vertex.* The distance *FV* from the principal focus to the vertex is called the *focal length of the mirror.*

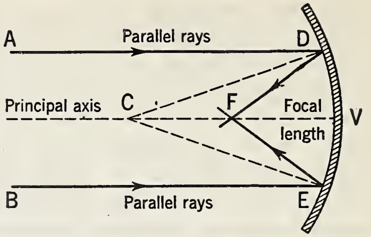


Fig. 450. Parallel rays are reflected to the principal focus.

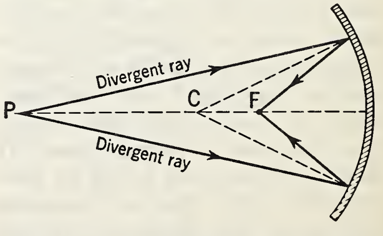


Fig. 451. Divergent rays are reflected as shown.

*Diverging* rays coming from a point $P$ on the principal axis will be brought to a focus on the principal axis, but the focus will be nearer the center of curvature than it is to the mirror. (See Fig. 451.) *Converging* rays are also focused by curved mirrors. Fig. 452 shows a case where they are focused upon the principal axis between the vertex and the principal focus.

**428. How can we construct the image of a point in a spherical mirror?** Look at Fig. 453. We wish to find the image of the point $P$ as formed by a concave mirror. First we shall draw the principal axis. Light is given off in all directions from the point $P$. Hence it is possible to draw *any two* lines to represent rays of light that fall upon the mirror, and then find where they intersect after reflection from the mirror. In all our construction work we must make the angles of incidence and reflection equal. The pupil will find it easier if we select for *one line* the secondary axis, since it is incident upon the mirror at an angle of 90°, and for that reason it is reflected directly back upon itself. Hence, we draw the secondary axis $PS$ from $P$ to the mirror. Then the image of the point $P$ must be at some point on the line $PS$. To find its exact position, we shall draw another line from $P$. For the *other line* to represent a ray of light from $P$ we shall choose the line $PB$, which is *parallel* to the principal axis. We select this line because we know that all rays parallel to the principal axis are reflected back to the principal focus, $F$. From the point of incidence of this line upon the mirror at $B$, this ray is reflected back through $F$ to $P'$. We have located the image of $P$ on the lines $PS$ and $BP'$. It must be at $P'$, the only point common to the two intersecting lines. To prove that $PB$ passes through $F$ when reflected, we may draw the normal $BC$, and show that the angle of incidence $PBC$ equals the angle of reflection $CBF$.

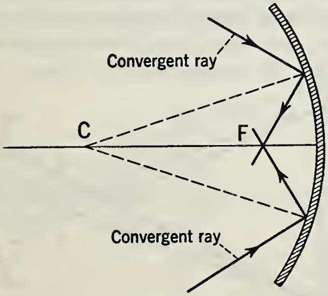


Fig. 452. Converging rays are reflected to meet nearer the mirror than the principal focus.

**429. How are images formed by concave mirrors?** We may construct the image of an object as formed by a concave mirror by locating the images of enough different points. If the object is an arrow, we can locate the image by finding the positions of the two points at its ends. Theoretically, we can consider the object as located at an infinite distance from the mirror and then see how and where the images will be formed as the object is made to approach the mirror. Thus, six fairly distinct cases may be studied:

Case 1. *Object at infinite distance.* If we could have an object at an in-

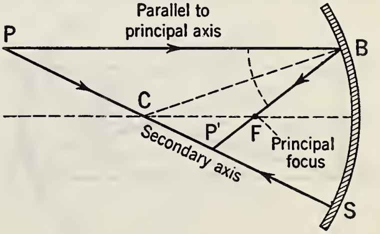


Fig. 453. How a concave mirror forms the image of a point.

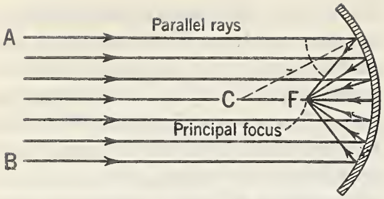


Fig. 454. Object at infinite distance. Image is a point. Case 1.

finite distance from the mirror, all the incident rays would be parallel. They would all be reflected back to the principal focus. (See Fig. 454.) Hence we conclude that *the image formed by a concave mirror when an object is at an infinite distance is a point at the principal focus.*

Case 2. *Object at finite distance beyond center of curvature.* Look at Fig. 455. We wish to locate the image of the arrow $AB$. We find the image of $A$ as discussed in the preceding section by drawing the secondary axis $AC$ and the parallel ray $AD$, which is reflected back through $F$ to form the image of $A$ at the point $A'$. In a similar manner we locate the image of $B$ at the point $B'$. The construction lines used to locate the image of $A$ are all numbered 1; those used to locate the image of $B$ are numbered 2. From the diagram, we see that *the image in this case is real, inverted, smaller than the object, and that it is formed between the center of curvature and the principal focus.* The nearer the object approaches the center of curvature, the larger the image becomes.

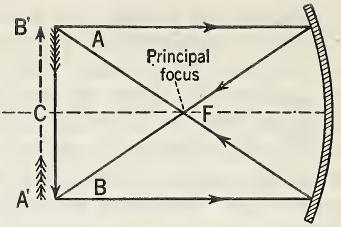


Fig. 456. Object and image both at center of curvature. Case 3.

Case 3. *Object at center of curvature.* When the object is at the center of curvature, as shown in Fig. 456, we find that the image of $A$ is formed at $A'$, a point coincident with $B$, and that the image of $B$ is at $B'$, a point coincident with $A$. To show the secondary axes in this case, we would need to make the aperture of the mirror 180°. *When the object is at the center of curvature, the image is real, inverted, the same size as the object, and located at the center of curvature.*

Case 4. *Object between center of curvature and principal focus.* This case is the converse of Case 2. As shown in Fig. 457, we use the same method of finding the image that we have used before. We observe that in this case the *image formed is real, inverted, larger than the object, and formed beyond the center of curvature.* The nearer the

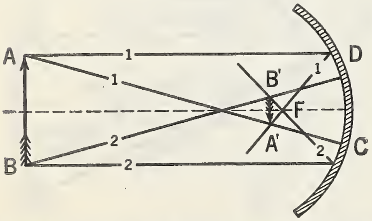


Fig. 455. Two lines are necessary to locate an image. Case 2.

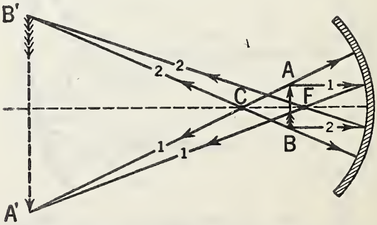


Fig. 457. Object between center of curvature and principal focus. Case 4.

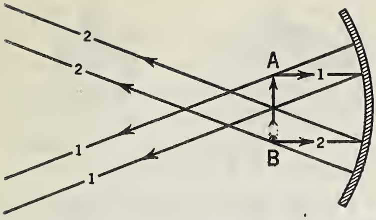


FIG. 458. Object at principal focus. No image formed. Case 5.

object approaches the principal focus, the larger the image becomes.

CASE 5. *Object at principal focus.* We observe that this case is the converse of Case 1. When we try to construct the image as in other cases, we find that the rays that are reflected from the mirror are parallel. (See Fig. 458.) *When the object is at the principal focus, no image is formed.* Perhaps a mathematician would say that an infinitely large image is formed at an infinite distance.

CASE 6. *Object between principal focus and mirror.* When we attempt to construct the image as in other cases, we find that the reflected rays which leave the mirror are *divergent.* They can never meet to form a *real* image. They *appear to meet behind the mirror to form a virtual image,* as shown in Fig. 459. In this case, *the image is virtual, erect, enlarged, and situated behind the mirror.*

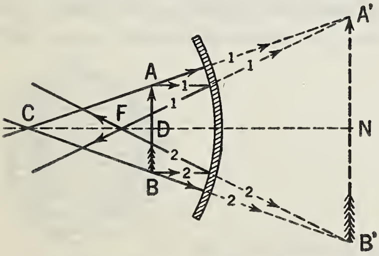


FIG. 459. Object between mirror and principal focus. Case 6.

**430. How do convex mirrors form images?** When we look into the convex mirror of the type used outside the windshield of some trucks, we see a small erect image of reduced size. We may use a diagram to show how such an image is formed. In Fig. 460, *AB* represents the object. The secondary axes are the radii *produced.* The parallel rays are reflected from the surface of the mirror and made divergent. The reflected rays *produced appear* to meet at the principal focus. With a convex mirror, *all images formed are virtual, erect, smaller than the object, and located between the mirror and the principal focus.* The size of the image is increased by bringing the object closer to the mirror, but it can never become as large as the object itself.

**431. What are the practical uses of curved mirrors?** We have seen that curved mirrors can be used in amusement parks to form fantastic images. The convex mirror, when used by automobile drivers, gives a wide field of vision, but the driver cannot judge the distance of a car approaching from his rear from the size or position of the image in the mirror. In a plane mirror, the image seems as far behind the mirror as the object is in front of the mirror. Some drivers use both a convex and a plane mirror.

Concave mirrors find use as reflec-

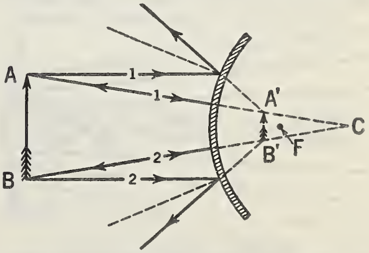


FIG. 460. Image formed by a convex mirror.

tors of light and also for forming images. We may use Cases 1 and 3 to find the focal length of the mirror. Since *the focal length is just half the radius,* we may double the focal length to find the radius of curvature. We may use Cases 2 and 4 to form images on a screen. The former gives a bright image of reduced size, while the latter case gives an enlarged image. When an enlarged image is formed, it always loses in brightness. The so-called shaving mirror is an application of Case 6. Your dentist also uses a small mirror of this type for examining your teeth.

If we place an electric light at the principal focus of a concave mirror, its rays will be reflected from the mirror along parallel lines. When the light is placed a little nearer the mirror than the principal focus, the rays will be slightly divergent, as shown in Fig. 461. Such a reflector is used in the headlights for automobiles, streetcars, and locomotives. The searchlight and spotlight may use a concave mirror, or lenses may be used to concentrate the light rays on a distant object.

Fig. 462 shows how different types of reflectors may be used to secure a proper distribution of light. Some reflectors are wide and flaring. Others of the bell-shaped type concentrate the rays on a smaller area.

The *ophthalmoscope* is a small concave mirror with a hole in its center. By using this instrument, a physician can reflect light into a patient's eye, and at the same time look into the eye through the hole in the mirror.

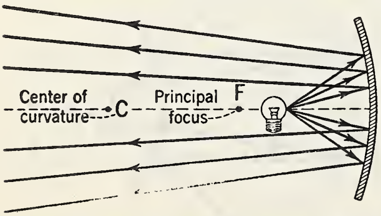


Fig. 461. Headlights and searchlights. Lamp is placed near principal focus.

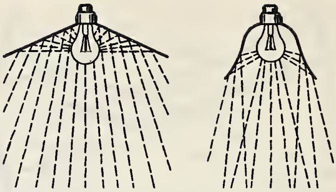


Fig. 462. Different types of reflectors.

**★432. What is spherical aberration?** If we use a mirror of *large aperture,* those parallel rays of light which fall upon the mirror near its edge are not reflected through the principal focus. They are focused at a point nearer the mirror. (See Fig. 463.) Only those parallel rays which are incident upon the mirror near its vertex are reflected to the principal focus. *The non-focusing of parallel rays at the principal focus is called spherical aberration. Such a wandering of the focus produces a distorted image.*

What are the remedies for spherical aberration? If the aperture of the mirror can be kept as small as 10° or 12°, the distortion of the image is negligible. A mirror of larger aperture may be used to collect more light rays, and an annular (*annulus,* ring) diaphragm of some opaque material can be used with it to cut off those rays near the edge which would cause dis-

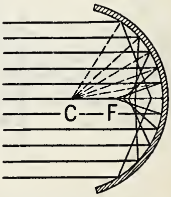


Fig. 463. Spherical aberration.

Rays do not all focus at one point

tortion. An adjustable diaphragm of this type is used with a camera lens for a similar purpose. A third method of preventing spherical aberration depends upon the use of a mirror whose surface is not a sphere, but has the curve of the parabola. Fig. 464 shows how parallel rays are all focused at a point by such a mirror. Headlights in automobiles are generally fitted with parabolic reflectors.

**433. How do the relative sizes of object and image compare?** In Section 422 we found that the relative size of the object and image depends upon their respective distances from the aperture. This was shown by the use of similar triangles. In the same manner, it is possible to show that the sizes of the object and the image formed by a curved mirror depend upon their relative distances from the center of curvature. (See Fig. 459.) For mirrors of small aperture, it is possible to show that the relative *sizes of the object and image depend upon their respective distances from the mirror.* Stated as a proportion, size of object ($S_o$): size of image ($S_i$) = distance of the object from the mirror ($D_o$): distance of image from mirror ($D_i$). Or,

$$S_o : S_i = D_o : D_i.$$

Of course, when an object is magnified or reduced in size, both the length and the breadth are changed proportionally.

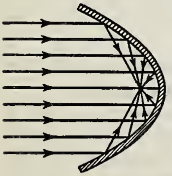


FIG. 464. There is no aberration when a parabolic mirror is used.

PROBLEM. An object 8 inches high is placed 3 ft. from a mirror. The image is formed on a screen 18 in. from the mirror. Find the height of the image.

*Solution.* By substituting in the formula, $S_o : S_i = D_o : D_i$, we have, $8 : x = 36 : 18$. Whence, $x = 4$ in., the height of the image.

**★434. How can we find distances of object and image in terms of the focal length?** As one might suspect from the various cases of image formation by concave mirrors, there is a mathematical relation between the distances of the object and image from the mirror and the focal length of the mirror. The derivation of such a formula is beyond the scope of secondary school work, but the formula is useful for solving problems. Using $D_o$ to represent the distance of the object from the mirror, $D_i$ to represent the distance of the image from the mirror, and $F$ for the focal length, then

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F}.$$

This formula may be used in all cases governing concave mirrors. When the answer is a negative quantity, the image is virtual.

For convex mirrors, both $\frac{1}{D_i}$ and $\frac{1}{F}$ are negative.

PROBLEM. An object is 6 ft. from a mirror whose focal length is 8 inches. Find the distance from the mirror at which the image is formed.

*Solution.* Substituting in the formula,

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F},$$

we have the following:

$$\frac{1}{72} + \frac{1}{D_i} = \frac{1}{8}.$$

Clearing of fractions,

$$D_i + 72 = 9D_i. \text{ Whence,}$$
$$D_i = 9 \text{ in.}$$

## Summary

The angles of incidence and reflection are equal, and they lie in the same plane.

Reflection from a polished surface is regular; from a rough surface, it is irregular or diffused.

Mirrors are plane or spherical; spherical mirrors may be concave or convex.

Images are real or virtual; a real image is inverted and can be thrown upon a screen. Virtual images are erect; they cannot be thrown upon a screen.

Images formed by plane mirrors are erect, virtual, the same size as the object, and as far behind the mirror as the object is in front.

A focus is a point where rays of light meet or from which rays of light diverge. Rays parallel to the principal axis are reflected to a point on the principal axis, midway between the center of curvature and the vertex. This point is the principal focus. Its distance from the vertex is the principal focal length. It equals half the radius of curvature of a concave mirror.

In concave mirrors, the image is a point when the object is at an infinite distance. As the object approaches the mirror, the real image formed increases in size, becoming equal to the object at the center of curvature, and infinitely large when the object is at the principal focus. If the object is brought nearer the mirror than the principal focus, the image becomes virtual.

The images formed by convex mirrors are erect, virtual, and smaller than the object.

Spherical aberration is the deviation from the principal focus of those rays of light that are reflected from the edge of the mirror. It may be remedied by using a diaphragm, or by having the mirror shaped like a parabola.

*How many of the following terms can you define or explain?* (*It is suggested that you try writing them.*)

Laws of reflection
Mirrors
Images by plane mirrors
Uses for mirrors
Aberration
Regular and diffused reflection
Images
Images by curved mirrors
Relative sizes of object and image
Real and virtual images

## QUESTIONS

1. Why can we look at the image of the sun in the water at noon, but not in the afternoon when the sun is low on the horizon?

2. Given two plane mirrors. Draw a diagram to show how a person on the north side of a house could use them to see a person on the south side.

3. What advantages does a plane mirror used as a driver's mirror have over a convex mirror? What advantages does a convex mirror have over a plane mirror?

4. Draw a diagram to show how two small mirrors can be placed in a tube to enable one of short stature to see over the heads of other persons in a crowd.

5. Explain how a too glaring headlight may be remedied.

6. The law of New Jersey specifies that no headlight may cast a beam of light that is higher than 4 ft. at a distance of 200 ft. In what two ways could you adjust a headlight that did not meet this requirement?

7. The manufacturing companies have stopped making electric bulbs of clear glass. Give a good reason.

8. The maximum candle power of a tungsten lamp is horizontal. In what way may this defect be remedied?

9. Why is the image formed by the bowl of a silver spoon distorted?

10. Lay a plain gold ring on a sheet of white paper. Note the shape of the image that is produced. How does this image, which is called the "caustic by reflection" illustrate spherical aberration? Compare this image with that formed by the inside surface of a glass of water resting on a white tablecloth when the light is strong.

11. What changes would one observe in his image as he approached: (*a*) A plane mirror? (*b*) A convex mirror? (*c*) A concave mirror?

12. The maximum candle power for use in automobile headlights is generally not more than 32. Do you think the law of inverse squares applies for such a headlight? Explain.

13. Formerly, electric bulbs were frosted on the outside. Now they are frosted on the inside. Give a reason.

14. Why does the small boy who uses a mirror to flash a beam of light into the teacher's eyes almost invariably get caught?

15. Use Reader's Guide to look up an article on the manner in which invisible films are being used to prevent glare from glass. Try to find an article dealing with the making of invisible glass. If an invisible film were used to coat the lenses of spectacles, would such a film reflect light?

## PROBLEMS

### Group A

1. The focal length of a mirror is 10 in. What is its radius of curvature?

2. A man runs toward a plane mirror at the rate of 10 feet per second. At what rate does he approach his image?

3. Given a room 20 ft. square. For general illumination, which would be better, an 80-C.P. lamp placed in the center or four 20-C.P. lamps, one four feet from each corner. Give two reasons for your answer.

4. An object is 4 ft. from a concave mirror whose focal length is 9 inches. How far away is the image? If the object is 2 ft. high, calculate the height of the image.

5. An object is 8 in. from a concave mirror whose focal length is 12 in. How far from the mirror is the image formed? How many times is the image magnified?

### Group B

6. A pinhole camera has a sensitive plate 4 × 4 in. The box is 6 in. long. How far away must a man 6 ft. tall stand for a full-length image to be formed?

7. An object is placed 12 in. from a concave mirror whose focal length is 10 in. How far distant is the image? What is the relative size of object and image?

8. A concave mirror has a focal length of 15 in. The object is placed 12 in. from the mirror. How far away is the image?

9. The radius of a concave mirror is 36 in. An object is 12 ft. away from the mirror. Where is the image formed? How tall is the image, if the object is 4 ft. high?

10. An object is 12 in. distant from a concave mirror whose radius is 20 in. How many times is the image magnified?

# *Light — Refraction*

## 1. Refraction of Light

**435. What is refraction?** When we fire a rifle at a target, we make use of the fact that light travels in straight lines. If, however, we should try to shoot a fish beneath the surface of the water, we would be likely to miss. Light travels in straight lines only when the medium through which it travels is of the *same optical density* throughout. Light rays are *bent out of their course* as they pass from water to air, or from air to water. *Such bending of light rays as they pass from one medium into another of different density is called refraction.* Because of refraction, fish appear to be higher in the water than they really are, thus making it difficult to shoot or to spear them. (See Fig. 465.)

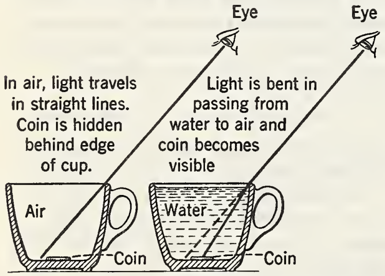

Eye
Eye
In air, light travels in straight lines. Coin is hidden behind edge of cup.
Light is bent in passing from water to air and coin becomes visible
Air
Coin
Water
Coin

Fig. 465. Observe how the water bends the light to make coin visible.

If we look down into a tall glass cylinder filled with clear water and place a finger on the side of the cylinder where the bottom appears to be, we shall find that the water is really deeper than it seems. In fact, you will probably find that you have placed your finger opposite a spot that is only three-fourths of the way to the bottom. Water is always deeper than it appears as we look down into it. When we step in the water on an uneven sidewalk or in the gutter, we find that it may come above our rubbers, although it seemed shallower.

A stick or a teaspoon placed in a tumbler of water appears to be bent or broken at the surface. Suppose we let *MN* of Fig. 466 represent the surface of a body of water. *AO* represents the path of a ray of light traveling through the air and falling upon the water at *O*. Instead of continuing along *OF* in a straight line, the ray of light is bent as it passes from air into water. It takes the path *OB*. The incident ray *AO* makes the angle *AOC* with the normal; it is called the *angle of incidence.* The refracted ray *OB* makes the angle *DOB* with the normal produced; it is called the *angle of refrac-*

---

### Vocabulary

Binocular, employing both eyes at once.

Refraction, the bending of rays of light which pass obliquely from one medium into another of different optical density.

Converging rays, rays which come together to meet at a point.

Diverging rays, rays which separate as they leave from a point.

*tion.* The angle *BOF* is called the *angle of deviation.* The pupil should remember that *a ray of light passing obliquely from one medium into another of different optical density is refracted.* If the ray of light is incident upon the other medium *at right angles, or along the normal, it is not refracted at all.*

**436. What causes refraction?** Suppose that we have five men marching abreast over a hard road. (See Fig. 467.) Their line of march, *AB*, carries them over a strip of marshy ground where their speed is retarded. The man at *R* enters the marsh land first and is the first to be retarded. Since the others continue at the same speed as before, the line of march now takes the direction *BC*. In the marshy ground all are equally retarded until the man *R* reaches harder ground and his speed increases. The line of march now takes the direction *CD*. The student will observe that as the speed decreases the line bends *toward* the perpendicular. An increase of speed on entering a new medium causes the line to bend *away from* the normal. It is evident that if the line of march were along the perpendicular, all would enter the marshy ground at once; they would therefore all be retarded at the same time and the line of march would not be bent. A dumbbell rolled across the floor will travel in a straight line, unless one of the balls is retarded more than the other; then it will be turned out of its course. If the right front wheel of an automobile which is going in a straight line enters a strip of soft ground, the wheels will turn, and the car will swerve to the right since the right front wheel is retarded.

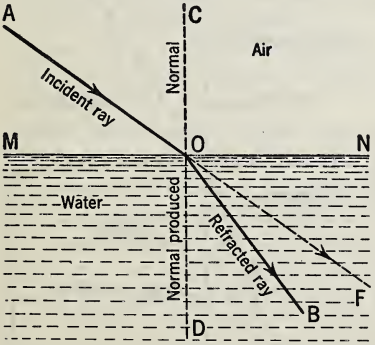


FIG. 466. Light is refracted as it travels from air into water.

Light travels more slowly in water than it does in air. Now we may picture a ray of light as having some thickness. Hence the edge of the ray which is first incident upon the water is the first to be retarded, and the ray is bent out of its course. Of course such bending will occur when the light enters any medium of greater optical density, in which the speed is retarded. The bending will occur in the opposite direction if the speed in the new medium is accelerated. Light rays incident upon the medium at an angle

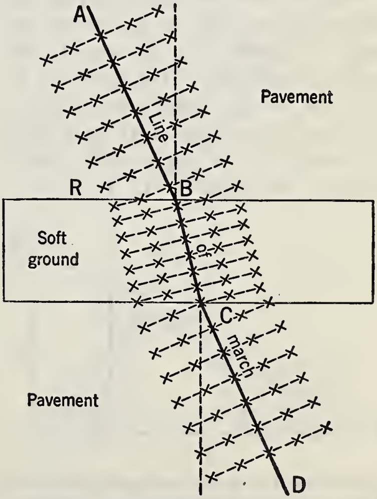


FIG. 467. The cause of refraction.

of 90° are all retarded or accelerated equally. Hence there is no bending.

**437. What is the index of refraction?** Fizeau and Foucault, two French physicists, were the first to make direct measurements of the velocity of light in air. In 1850, Foucault proved that light travels faster in air than it does in water. The speed of light in water is almost 140,000 miles per second, just $\frac{3}{4}$ as fast as in air. The speed of light in ordinary glass is about 124,000 miles per second, only about $\frac{2}{3}$ the velocity of light in air. *The ratio of the speed of light in air to its speed in another substance is called the index of refraction for that substance.* For example, the index of refraction for glass equals $\frac{\text{speed in air}}{\text{speed in glass}}\cdot$ The value for glass is $\frac{3}{2}$, or 1.5. Since the speed of light in water is only three fourths as great as in air, the index of refraction of water is $\frac{4}{3}$, or 1.333. The index of refraction of a few common substances is given in Table 14, Appendix B.

★The index of refraction may also be defined as the ratio of the *sine* of the angle of incidence to the *sine* of the angle of refraction. Let us refer to Fig. 468. In the right triangle *ABC*, the sine of the angle *BAC* is defined as the ratio of the length of the side *a*, opposite the angle *BAC*, to the hypotenuse, *c*. Enlarging the triangle without changing the size of the angle *BAC* does not affect this ratio, since the quotient of $\frac{a'}{c'}$ exactly equals that of $\frac{a}{c}\cdot$ A table of sines for the angles from 0 to 90° is given in Appendix B.

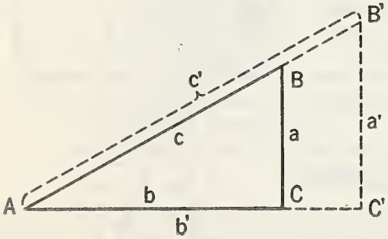


Fig. 468. The sine of an angle is the ratio of the side opposite the angle to the hypotenuse.

In Fig. 469, the line *AO* represents a ray of light traveling through the air and incident upon a glass plate at *O*. This ray is refracted as it enters the glass and moves along the path *OB*. To find the index of refraction, we first draw the normals *OP* and *OP'*. The index of refraction between the air and the glass is equal to the sine of the angle *AOP*, the angle of incidence, divided by the sine of the angle *BOP'*, which is the angle of refraction.

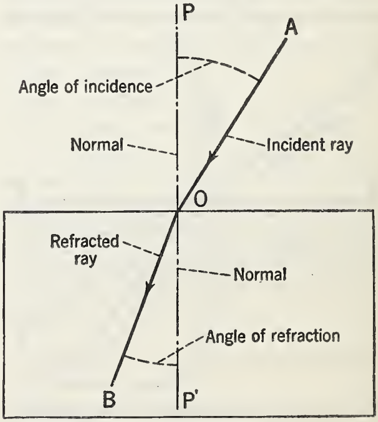


Fig. 469. How to measure index of refraction.

**438. How can the index of refraction be useful?** The index of refraction of pure transparent substances is a constant quantity. Hence we can identify substances by measuring their index of refraction, and we can also check their purity. An instrument called a *refractometer* has been so constructed that the index of refraction can be measured quickly and accurately. For example, butter fat and oleomargarine have different indexes of refraction. One of the first tests made in a food-testing laboratory to determine whether butter has been adulterated with oleomargarine is the measurement of the index of refraction. The exceedingly high index of refraction of the diamond furnishes one of the most positive tests for its identification. The diamond has an index of refraction of almost 2.5, while the best imitations have a refractive index of only about 2.

**439. What are the laws of refraction?** Some of the facts which we have learned in the preceding sections may be summarized as the LAWS OF REFRACTION. We observed that the speed is reduced when light passes from a rarer to a denser medium and that the speed is increased as it passes from a denser to a rarer medium.

LAW 1. *When a ray of light passes obliquely from a medium of lesser to one of greater optical density, it is bent toward the normal.* (A decrease in speed.) Conversely, *a ray of light passing obliquely from a denser to a rarer medium is bent from the perpendicular to the surface.* (An increase in speed.)

LAW 2. *The angles of incidence and refraction lie in the same plane.*

LAW 3. *The index of refraction for any two media is constant, no matter what the angle of incidence.*

**★440. How can one trace a ray of light through a glass plate?** If we know the index of refraction, it is possible to show the path that a ray of light takes as it passes through another medium. In Fig. 470, we may let *MNTP* represent a piece of plate glass and *AO* a ray of light incident upon the plate. From *O* as a center, let us describe two arcs having the ratios 3 and 2, the index of refraction of glass. Draw the normal *OR* and the line *BC* parallel to it, passing through the point where the incident ray intersects the *smaller* arc. The line *OD* which is determined by the points *C* and *O* marks the path taken by the refracted ray as it travels through the glass.

If the ray were not refracted as it leaves the glass, it would pass along the line *DS*. To show how it is refracted, from *D* as a center we draw arcs having the same ratio as before. Draw the normal *DE*, and a line *xy* parallel to the normal. This time we draw the parallel line through the point where the *larger* arc is intersected by the refracted ray *produced*. The line *Dx* shows the path which the refracted ray takes as it leaves the glass.

If the ray of light *AO* is incident upon a triangular glass prism, as shown in Fig. 471, it is bent toward the perpendicular, and travels along the line *OB*. As the light leaves the prism, it is refracted from the perpendicular along the line *BC*.

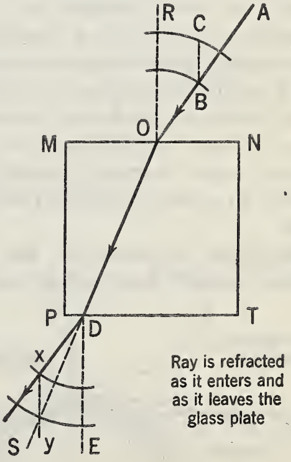

R
C
A
B
O
M
N
P
T
D
x
S
y
E
Ray is refracted as it enters and as it leaves the glass plate

FIG. 470. How to trace a ray of light through a glass plate.

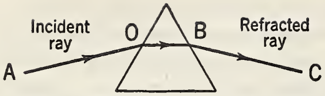


Fig. 471. The path that a ray of light takes as it passes through a prism.

**441. What is atmospheric refraction?** Light travels somewhat faster in a vacuum than it does in air. As the light approaches us from the sun or the stars, it will be refracted as it enters the earth's atmosphere. But since the light enters an atmosphere that gradually grows denser and denser, a ray of light coming from the sun or some other celestial body follows a path similar to the curve shown in Fig. 472. The refraction is gradual, instead of one distinct bend at the inter-surface of the two media.

On account of atmospheric refraction, we do not see the sun or stars in their true positions except when they are directly overhead at the zenith. We see the sun in its true position at noontime, if its rays are vertical. In the figure, we see the setting sun at $S'$, instead of in its true position at $S$. The refraction of light by our atmosphere makes the sun at this time appear about one diameter higher than it really is. Since the index of refraction from ether to air is only 1.00029, naturally the diagram must be greatly exaggerated to show on so small a scale any bending at all.

**442. What is meant by the term "critical angle"?** A ray of light passing from a denser to a rarer medium is bent *from* the perpendicular. In Fig. 473, suppose we have the incident ray *AO*, traveling from water to air and bent *from* the perpendicular along the line *OB*. Let us inquire what will happen to the refracted ray if we increase the angle of incidence *AOC*. Of course the angle of refraction will be greater than before, because the refracted ray is bent farther from the perpendicular. If we continue to increase the angle of incidence, a point is finally reached where the refracted ray *does not enter the air at all* but takes the path *ON*, coincident with the water surface, and making the *angle of refraction 90°. That particular angle of incidence at which the ray when refracted makes an angle of 90° with the normal is called the critical angle.* The critical angle for water occurs when the incident ray *DO* makes an angle of 48.5° with the normal. The critical angle for crown glass is 42°, and for the diamond it is only 24°.

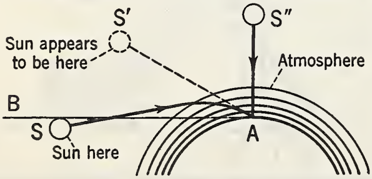


Fig. 472. The air refracts light passing obliquely through it.

**443. What is total reflection?** Of course it is possible to increase the angle of incidence of a ray passing from water to air beyond the critical angle. What will happen, then, to the refracted ray? It will not enter the air at all, but it will be *totally reflected* from

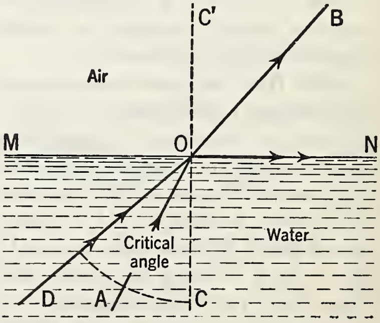


Fig. 473. What is the critical angle?

the water surface. In Fig. 474, we have represented a ray of light traveling along the path *EO*, making the angle of incidence *EOC greater* than the critical angle. The ray of light is turned back into the water medium along the line *OE′*. Of course in this case the angle of reflection equals the angle of incidence. *Total reflection always occurs when the angle of incidence exceeds the critical angle.*

**444. How can total reflection be made useful?** In the diamond, for example, where the critical angle is only 24°, much of the light entering the diamond is totally reflected. This makes it the most brilliant gem known. It is set in platinum, too, a good reflector, to help enhance its brilliancy. By adding lead to glass during its manufacture, its index of refraction is increased decidedly. Cut-glass dishes and brilliants are made from such glass. By increasing the index of refraction, we increase total reflection.

When a ray of light enters a right-angle glass prism like that shown in Fig. 475, it is totally reflected. The periscope of a submarine has two such prisms. The observer at *D* sees objects along the line *AB*. The light rays are reflected down the tube by the first prism, and then reflected at right angles by the second prism. The right-angle prisms are much more effective than two mirrors would be if set in the same position, because a mirror reflects only about 70% of the light it receives.

In high-grade field glasses, right-angle prisms are used to give a wider range of vision. Sometimes they are used to reinvert an image and make an inverted image erect. Right-angle prisms are also used in reflecting telescopes and for the range finders on battleships.

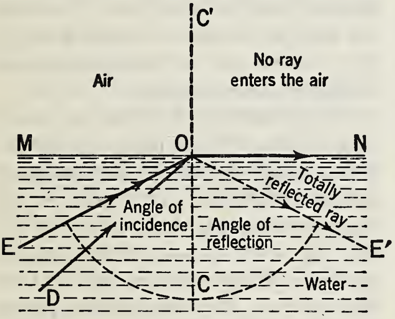


Fig. 474. Total reflection occurs when the critical angle is exceeded.

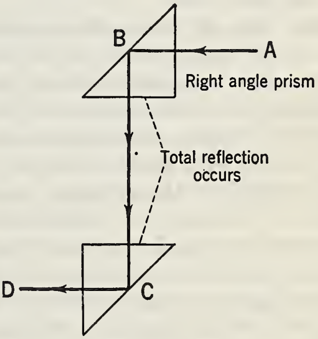


Fig. 475. Total reflection is used in the prisms of a periscope.

## 2. Lenses and Images

**445. What is a lens?** A portion of any transparent substance can be used as a lens. It must be bounded by two non-parallel curved surfaces, or by one plane surface and one curved. Lenses are nearly always made of glass. They are of two kinds:

1. *Converging.* Lenses of this type

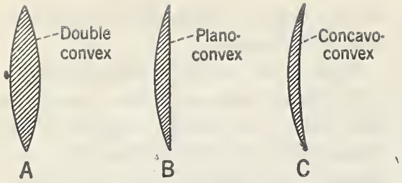


FIG. 476. Converging lenses are thicker at the center. *A*. Double convex. *B*. Plano-convex. *C*. Concavo-convex.

are shown in Fig. 476. They are always thicker in the middle than they are at the edges. Such lenses tend to bend rays of light so that they will converge and form a real focus. The lenses of *A* and *B* of the figure are called *flat* lenses; *C* shows a *meniscus* lens.

2. *Diverging*. When a lens is thicker at the edges than it is in the middle, it tends to make rays of light more divergent. The double concave lens and the plano-concave lens of Fig. 477 are *flat* lenses. The convexo-concave lens is a *meniscus* lens.

**446. How do lenses affect light?** A ray of light incident upon the center of a lens passes through it without being refracted at all. It is bent out of its course if it passes through any other part of the lens. In Fig. 478, the ray *AD*, parallel to the principal axis, is bent at *D* toward the normal as it enters the lens; at *E* it is bent from the normal as it leaves the lens. *Parallel rays of light are so refracted by converging lenses that they meet at a point called the principal focus.* If converging rays of light fall upon such a lens, they are made more converging and are brought to a focus at a point nearer the lens than the principal focus. Diverging rays incident upon such a lens are made less divergent. Very divergent rays cannot be brought to a *real focus*, but slightly divergent rays may be brought to a focus at some point beyond the principal focus.

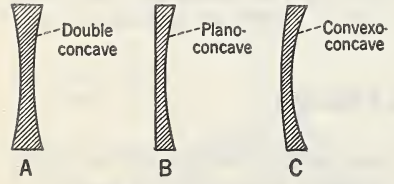


FIG. 477. Diverging lenses are thicker at the edges. *A*. Double concave. *B*. Plano-concave. *C*. Convexo-concave.

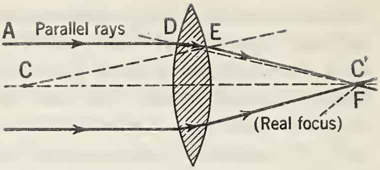


FIG. 478. How converging lenses focus paralled rays. Case 1.

From Fig. 479 we see that diverging lenses tend to scatter rays of light. Parallel rays are made divergent; they appear to meet to form a *virtual focus*, as shown by the dotted lines. Converging rays are made less convergent by such lenses, and diverging rays are made still more divergent.

**447. Definition of terms is necessary.** Before we can study the formation of images by lenses, we must learn several definitions. In many lenses, there are two *centers of curvature, CC′*. (See Fig. 480.) In this case they are the centers of the intersecting spheres that form the lens. The *principal axis* passes through the centers of curvature. The

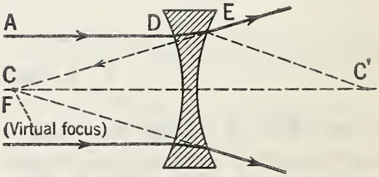


FIG. 479. How diverging lenses focus parallel rays.

ray of light $AB$ is refracted and passes through the principal focus $F$. *In lenses the secondary axes pass through the optical center of the lens;* the optical center $O$ practically coincides with the geometrical center of the lens. The ray $AOA'$ is an example of a secondary axis drawn from $A$. Rays of light passing through the optical center *are not refracted.*

Similar to curved mirrors, lenses refract parallel rays so that they meet at the *principal focus*, but this focus is *not midway* between the lens and the center of curvature. Its position on the principal axis will depend upon the index of refraction of the lens. With a double convex lens of crown glass, the principal focus and the center of curvature are almost coincident. With such a lens, the radius of curvature and the *principal focal length* are almost equal. Increasing the index of refraction shortens the focal length. The thicker the lens, the shorter the focal length, but in this case the radius of curvature is also reduced.

**448. How do lenses form images?** By a study of Fig. 480, we may learn how images are formed by lenses. $CC'$ represent the centers of curvature of the lens $L$. We wish to show how the image of the point $A$ is formed. Here again it will be necessary to use two rays coming from $A$ and see how they are focused by the lens. For one ray of light we may choose the secondary axis, since it is not refracted as it passes directly through the optical center, $O$. For the other ray we may select $AB$, parallel to the principal axis. At $B$ this ray is refracted, being bent again as it leaves the lens at $D$, and passes through the principal focus, $F$, which is coincident with $C'$. Thus we locate the image of $A$ at $A'$ where the ray refracted through the principal focus meets the secondary axis, $AA'$.

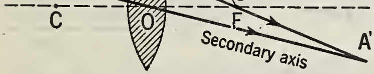


Fig. 480. Terms pertaining to lenses.

The student must keep in mind several differences between lenses and mirrors.

1. Secondary axes pass through the optical centers of lenses, not through the centers of curvature.
2. The principal focus is at or near the center of curvature; this makes the focal length practically equal to the radius, whereas in mirrors it is equal to half the radius.
3. Since the image is formed by rays of light that pass through the lens, a *real* image is formed on the side of the lens opposite the object, just the reverse from mirrors. *Virtual* images formed by lenses appear to be on the same side of the lens as the object.
4. Convex lenses form images in almost the same manner as concave mirrors; concave lenses are like convex mirrors in the manner in which they form images.

**449. How are images formed by convex lenses?** Here, too, we may consider six different cases, assuming that an object is brought toward the lens from an infinite distance by several successive steps.

Case 1. *Object at infinite distance.* We have all used a burning glass to focus the sun's heat rays upon a point. Light rays focus in the same manner. While the sun is not at an infinite distance, yet it is so far away that its rays are nearly parallel. When the object is at an infinite distance so that its

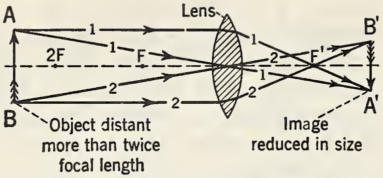


FIG. 481. Object at a finite distance. Image reduced in size. Case 2.

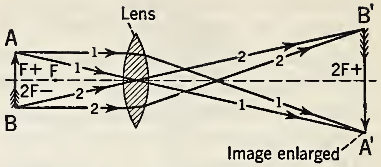


FIG. 483. Object between *F* and 2*F*. Image enlarged. Case 4.

rays are parallel, *the image formed is a point at the principal focus.* This case has no practical value for image formation. It may be used *to find the focal length of a lens.* When the sun's rays are focused on a white screen, the distance from the screen to the lens is the *focal length of the lens.*

CASE 2. *Object distant from lens more than twice focal length.* Look at Fig. 481. The secondary axes are drawn from *A* and from *B*. They are not refracted. Rays parallel to the principal axis are also drawn from *A* and from *B*. They are refracted and pass through the principal focus, meeting the secondary axes at *A′* and *B′* to form the image *A′B′*. In this case, we find that the *image is real, inverted, smaller than the object, and distant from the lens more than once and less than twice the focal length.* The lenses of the eye, the camera, and the telescope, where small, bright, well-defined images are needed, are all applications of this case.

CASE 3. *Object distant twice focal length.* Just as we constructed the image of Fig. 480, so we may construct the image for this case. From Fig. 482 we see that *the image is real, inverted, the same size as the object, and at a distance from the lens equal to twice the focal length.* If we have an inverted image and wish to turn it upside down without changing its size, this case is applicable. It is used in the field telescope.

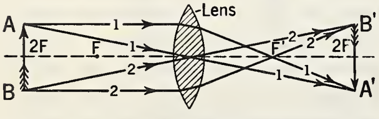


FIG. 482. Object is distant twice the focal length. Image same size. Case 3.

CASE 4. *Object distant more than once and less than twice the focal length.* This case is the converse of Case 2. From Fig. 483 we see that *the image is real, inverted, enlarged, and distant more than twice the focal length of the lens.* The compound microscope, the optical lantern, and the motion picture projector are all applications where a lens is used as in this case.

CASE 5. *Object at principal focus.* This case is the converse of Case 1. If the pupil draws a diagram, he will find that the rays of light are parallel as they leave the lens. *No image is formed.* If a lamp is placed at the principal focus of a lens, as shown in Fig. 484, its rays leave the lens as a beam of light. The lighthouse and the searchlight are applications of its use.

CASE 6. *Object distant from lens less than one focal length.* Look at Fig. 485.

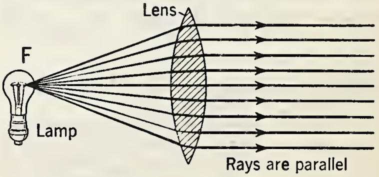


FIG. 484. When object is at *F*, emergent rays are parallel. Case 5.

We see that the rays are divergent as they leave the lens. No real image can be formed. If the eye is placed close to the lens, a *virtual, erect, enlarged image* can be seen on the same side of the lens as the object. This image can never be thrown upon a screen. The simple magnifier, and the eyepieces of microscopes and telescopes all make use of this method of forming images.

**450. How do concave lenses form images?** Concave lenses tend to scatter light rays. The only kind of an image that can be formed by a concave lens is *virtual, erect, and reduced in size.* Such lenses are used to neutralize the effect of a convex lens, or to reduce to some extent the converging effect of convex lenses.

**451. What is spherical aberration?** When we use a camera on a bright day we nearly close the diaphragm so that light can pass through the central part of the lens only. This gives an image that is well-defined. On a darker day we open the diaphragm more to let in more light. The image is not so distinct and clear-cut, since the rays of light that pass through a lens near the edge do not meet quite at the principal focus. Spherical aberration is a defect of lenses just as it is of spherical mirrors. (See Fig. 486.)

The diaphragm is used to correct spherical aberration in lenses. With the camera it is adjustable. The lens may be so ground that its surface has the shape of a parabola. A lens that is corrected for spherical aberration in this manner may be used with the diaphragm wide open. Such lenses are known as "high-speed" lenses.

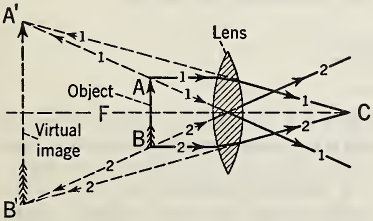


Fig. 485. Object between *F* and the lens. Image enlarged. Case 6.

**452. How can we find the relative sizes of image and object?** We may use the same formula to find the relative sizes of object and image with respect to their distances from a lens that we did for curved mirrors. The letters $S_o$ and $S_i$ in the following formula represent the sizes of object and image, while $D_o$ and $D_i$ represent the distances respectively of object and image from the optical center of the lens.

$$S_o : S_i = D_o : D_i.$$

**453. How are distance of object and image related to focal length?** We may use the same formula that we used with curved mirrors when we wish to find the distances of the object and image from a lens in relation to its focal length. If we use $D_o$ to represent the distance of the object from the lens, $D_i$ to represent the distance of the image from the lens, and $F$ to represent the focal length of the lens, then we have the following formula:

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F}.$$

When the answer is a negative one, the image is virtual. For concave lenses, both $\frac{1}{D_i}$ and $\frac{1}{F}$ are negative.

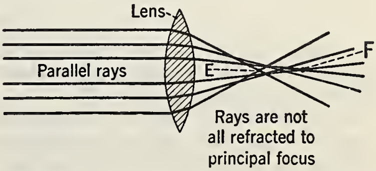


Fig. 486. Spherical lenses produce aberration.

## Summary

Refraction is the bending of a ray of light out of its course as it passes obliquely from one medium into another of different optical density. When passing into a more highly refractive medium, it is bent toward the perpendicular, and conversely.

The index of refraction of any substance is the ratio of the speed of light in air to its speed in that substance.

That especial angle of incidence at which the refracted ray is perpendicular to the normal is called the critical angle. Total reflection occurs when the angle of incidence exceeds the critical angle.

In the manner in which they form images, convex lenses are analogous to concave mirrors; concave lenses are analogous to convex mirrors.

Spherical aberration, which occurs in lenses as well as in mirrors, may be remedied by the use of a diaphragm.

The formulas used for finding relative sizes of object and image in terms of their relative distances from mirrors may also be used for lenses. The formula, $\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F}$ may also be used as a lens formula.

*How many of the following terms and phrases can you define or explain? (A large vocabulary will always be useful.)*

Refraction
Index of refraction
Critical angle
Atmospheric refraction
How lenses form images
Causes of refraction
Laws of refraction
Total reflection
Kinds of lenses
Relative distances of object and image from lens
Meniscus lenses

## QUESTIONS

1. Give a reason why the sun is visible after it sinks below the horizon.

2. In making microscopic slides, Canada balsam is used to cement the cover glass to the slide. Give one good reason.

3. Flint glass is used in making cut glass. What advantage has it over crown glass?

4. What effect would immersion in water have upon the focal length of a convex lens?

5. Draw a diagram to show how a lantern must be constructed to throw a beam of light in practically one direction only.

6. Objects are practically invisible when immersed in a liquid that has the same index of refraction. How can carbon disulfide be used to distinguish between real diamonds and paste diamonds, which are made of flint glass?

7. Give one reason why you would expect to see the sun before it rises above our horizon. Explain why one sees the sun in its true position only at midday.

## PROBLEMS

### GROUP A

1. How fast does light travel in the diamond? What is its speed in crown glass? What is its velocity in olive oil?

2. If the speed of light in a transparent medium is 105,000 miles per second, what is the index of refraction of that medium?

3. A candle is 8 ft. from a double convex lens of 8 in. focal length. How far from the lens is the image formed? What is the height of the image if the object is 12 in. tall?

4. An object placed 80 cm. in front of a double convex lens forms a distinct image on a screen 25 cm. on the other side of the lens. What is the focal length of the lens?

### Group B

5. An object is 30 cm. in front of a convex lens whose focal length is 50 cm. How far away is the image formed? How does it compare in size with the object?

6. A convex lens has a focal length of 15 cm. An object is 20 cm. from the lens. How far from the lens is the image formed? If the object is 30 cm. high, how tall is the image?

7. A picture is 5 × 6 in. What is the size of the image of this picture if it is placed 9 in. from a convex lens of 8 in. focal length? What is the size when the focal length is 6 in.?

8. The image of an object 4 ft. high is formed on a screen 3 in. high. How far away must the object be placed from the lens to form a full-length image on the screen, which is placed 18 in. from the lens? What focal length lens must be used?

# *Light — Optical Instruments*

**454. We use many optical instruments.** As you read this page, you are using the best of optical instruments, the eyes themselves. To enable the eye to gather more light and see at greater distances, we make use of telescopes. To help us to examine more carefully tiny objects, we use the microscope to make them appear larger. For our edification or amusement, we use an optical lantern or a motion picture machine to throw enlarged pictures on a screen. For reflectors in house lighting we use mirrors, and we use mirrors and lenses for headlights. For spectacles needed to aid the eyes, we use lenses of different kinds as optical instruments. Many optical instruments have a *combination of lenses.* In describing optical instruments in this chapter, we shall use a single lens for the sake of simplicity, and only the secondary axes will be shown in some of the drawings.

**455. What is the structure of the human eye?** In many respects the eye is the most perfect optical instrument. Let us examine Fig. 487 to learn something of its structure. There are several parts.

1. *The white coat.* This outer coat of the eyeball is hard and tough. It preserves the shape of the eyeball and protects the eye from injury.

2. *The middle coat.* This coating of the eye contains a black pigment. Its purpose is to absorb stray rays of light and prevent the blurring of the image by reflection from the walls. It is of interest to note that the interiors of nearly all optical instruments are painted black.

3. *The inner coat.* The *retina,* or inner coat of the eye, covers the back portion of the eyeball only. The nerves of the eye are spread out upon the retina, forming a sensitive screen to receive the image.

4. *The crystalline lens.* This double convex lens finds use in forming upon the retina a *real* image of the object at which one is looking.

5. *The iris.* The colored portion of the eye is called the iris. It serves as a diaphragm to cut off the rays of light from the edge of the lens. A hole in the

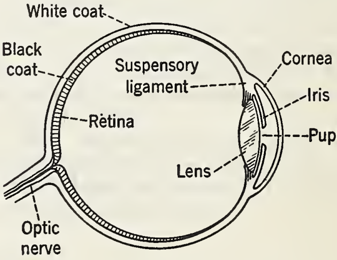


Fig. 487. The structure of the eye.

## Vocabulary

Anastigmat, a lens combination which is corrected for astigmatism.

Annular (*annulus*, a ring), ring-shaped.

Diaphragm, an annular disc used to keep rays of light from passing through the edges of a lens.

Meniscus, crescent-shaped.

Photo-electric, a tube in which light waves of varying intensity will cause a variation of the electric current.

Camouflage, a method of deceiving the eye.

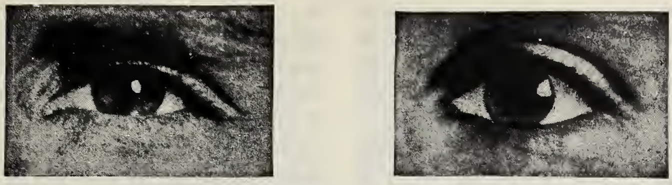


FIG. 488. The pupil at the left is contracted in strong light. At the right, the pupil in subdued light is expanded.

center of the iris is called the *pupil.* In a dark room the pupil becomes larger to admit more light, as shown at the right of Fig. 488. In bright sunlight, it contracts until it is about the size of a pinhead. (See Fig. 488.) The eye is filled with watery or jelly-like humors which aid in the formation of images. The eyelids act as a shutter to screen out the light.

**456. How does the eye form images?** Of course, the object is distant from the lens of the eye more than twice its focal length. Hence the lens forms upon the retina a *real, inverted, small* image. It is bright and well-defined or clear-cut. (See Fig. 489.) The lens of the eye has considerable *power of accommodation.* It is supported by a muscle which can make it more rounded when necessary. Increasing the convexity of the lens in such manner shortens its focal length. *Hence the eye is self-focusing.* If an object is brought close to the eye, the muscle contracts, and the increased convexity of the lens makes it possible for the eye to see nearby objects clearly. In the normal eye, the lens can be made convex enough to enable one to see clearly objects as close as 10 in., or 25 cm. This distance is known as the *nearest distance for distinct vision.*

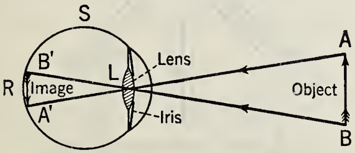


FIG. 489. How the lens of the eye forms images.

When one reads for a long time, the muscle which keeps the lens properly focused becomes tired. When the muscle relaxes, the lens becomes flatter and more distant objects come into focus. After one has been reading a long time, he may rest his eyes by looking at a distant landscape.

**457. How are defects of the eye corrected?** We have seen that the normal eye is "self-focusing," since the muscles in the eye are able to change the shape of the crystalline lens enough to make the image fall upon the retina, whether the object is nearby or remote. Some persons are *nearsighted.* Either the eyeball is too elongated, or the lens is so convex that the image is formed in front of the retina. Only when the object is brought very close to the eye, so that its rays are diverging when they reach the lens, will such an eye give distinct vision. (See Fig. 490.)

The defect called nearsightedness can

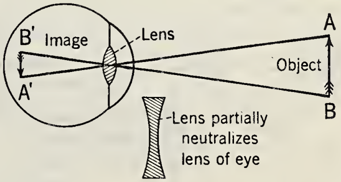


FIG. 490. Nearsightedness is remedied by the use of concave glasses.

be corrected by wearing glasses which *partially* neutralize the abnormal convexity of the lens of the eye. Such glasses have concave lenses which make the rays of light more divergent before they enter the eye. Many children who are slightly nearsighted are likely to have normal eyes when they reach maturity.

If the eyeball is too short, or if the lens is too flat, *farsightedness* will result. In order to have the lens form the image on the retina instead of behind it, the object must be held at considerable distance. It is not uncommon to see a middle-aged person holding a paper at arm's length when reading. The lens in his eye has lost to some extent the power of accommodation. (See Fig. 491.)

In order to correct farsightedness, glasses with convex lenses are worn. Such glasses make the light rays more convergent before they enter the eye and then the lens of the eye forms the image upon the retina. Glasses with double lenses, called *bi-focals*, are sometimes used to enable a person to read with one set of lenses and to see more remote objects clearly with the other set.

If the surface of the *cornea*, which is the somewhat bulging front portion of the eyeball, is not perfectly curved, or if the lens itself is somewhat irregular, then all parts of an object will not be in focus at the same time. To such an eye, the lines of Fig. 492 do not all appear equally distinct at one time. Some of the lines are in focus, but the others form a blurred image. This defect in vision is known as *astigmatism.* To correct the defect, glasses which have especially ground lenses to counteract these irregularities must be worn.

**458. Why are meniscus lenses used?** If the *flat lenses* of Figs. 476 and 477 are used in eyeglasses, the wearer does not get a clear image unless he looks through the center of the lens. Thus he is forced to turn his head from side to side, or up and down, in order to see objects clearly. The letters in the center of Fig. 493 are in focus with such a lens, but those around the outer edges are not. There is still another objection to the flat lens. Its center is nearer the eye than its edges. (See Fig. 494.) Unless the glasses are set farther from the eye than they should be the eyelashes will brush against the glass, and cause annoyance.

The lenses C of Figs. 476 and 477 are both *meniscus lenses.* With lenses of this type in his glasses, the wearer has a fairly wide range of vision without the necessity of turning his head to

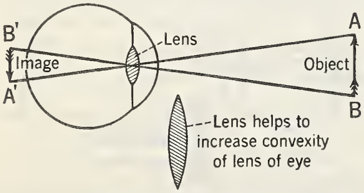
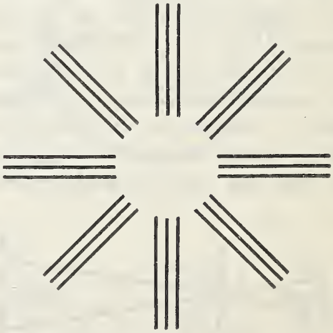
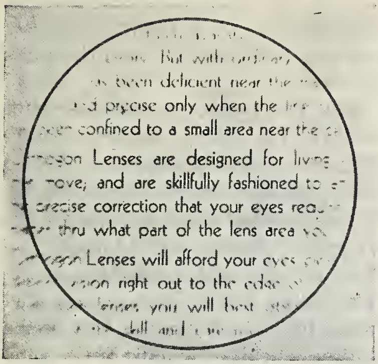


Fig. 491. Farsightedness is remedied by the use of convex glasses.



Do all the lines appear equally distinct?

Fig. 492. The lines are not all equally distinct if the eye has astigmatism.



*Courtesy of Bausch and Lomb Optical Company*

FIG. 493. Flat lenses form distinct images through their centers. Objects at one side are blurred.

see clearly. (See Fig. 495.) The meniscus lens of Fig. 494 conforms to the shape of the eyeball much better than the flat lens in the same figure.

**459. How do we judge size?** We all know that a man at a distance of a quarter of a mile appears so small that one may mistake him for a boy. A half dollar held an arm's length distant seems as large as the sun at its distance of over 92,000,000 miles. If we study Fig. 496, we see that the image of *AB* that is formed on the retina is larger than the image formed by *A′B′*. Both have the same length, but *A′B′* is twice as far away. The *visual angle ACB* is larger than the angle *A′CB′*. Hence *AB* appears larger than *A′B′*. When one knows the distance, he can estimate the size of an object. Much experience is needed before a person can estimate size and distance. A baby reaches for the moon and cries because he cannot get it. Later he learns to estimate distance by means of intervening objects. When the moon is rising or setting, intervening objects enable him to judge more accurately its size and distance.

**460. How do we estimate distance?** In the preceding section, we found that one learns to judge the size of an object from the size of the visual angle. The result, however, depends upon a knowledge of the distance, too. Conversely, if one knows the size of an object, he can estimate distance. To show that the method of estimating distance by the size of the visual angle is not very accurate, one may try the following: Close one eye and try to stick a pin in the center of a letter *O* placed in the center of a blank sheet of paper held at arm's length. You will probably miss the center by a quarter inch or more.

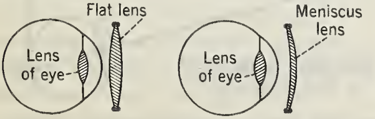
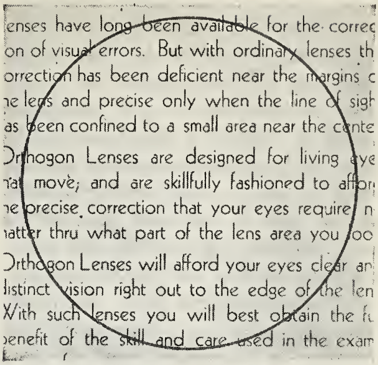


FIG. 494. How flat lenses differ from meniscus lenses.



enses have long been available for the correc
on of visual errors. But with ordinary lenses th
orrection has been deficient near the margins
e lens and precise only when the line of sigh
as been confined to a small area near the cente
rthogon Lenses are designed for living eye
at move; and are skillfully fashioned to affor
e precise correction that your eyes require n
atter thru what part of the lens area you loo
rthogon Lenses will afford your eyes clear an
istinct vision right out to the edge of the len
ith such lenses you will best obtain the f
enefit of the skill and care used in the exam

*Courtesy of Bausch and Lomb Optical Company*

FIG. 495. A meniscus lens gives a fairly distinct image, even from an angle.

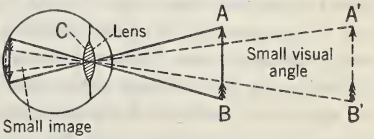


FIG. 496. Apparent size of an object depends upon its distance.

If you repeat the experiment with both eyes open, you will probably hit the center almost exactly. Another experiment may be tried to show the importance of *binocular vision.* If the teacher stands in front of a blackboard in the front part of the schoolroom and extends his arm, a pupil directly in front of him, but in the back part of the room, cannot judge how far the teacher's hand is from the blackboard, *provided he keeps one eye closed.* With both eyes open, he can judge fairly accurately. In binocular vision, we see a little more of the right side of a three-dimensional object with our right eye, and a little more of the left side with our left eye. Thus we get depth of vision or perspective.

From Fig. 497, we see that the eyes are rolled inward to some extent when we focus both eyes upon the point *D.* A certain amount of muscular effort is used in such a case. By experience we learn to estimate the distance *CD* by the angles *CAD* and *CBD.* The distance between the eyes is the base line from which we learn to estimate distance by the amount of muscular effort needed to roll the eyes inward until both are focused on the object. To be a good automobile driver, one must be able to judge distances well. If you have three one-inch cubes placed upon a table, you should be able to tell if one of them is only an inch farther from you when you are some 18 or 20 ft. distant.

Battleships find the range at sea by using for the base line a tube 12 to 15 ft. long. At each end of the tube there is a total reflecting prism. These prisms are focused upon the distant object, and the angles they make with the base line are carefully measured. Then the distance, which corresponds to the altitude of the triangle, is computed by trigonometry. Such *range finders* are generally calibrated to read distances directly.

**461. The camera is modeled after the eye.** The pinhole camera, Section 422, or the camera obscura, is said to have been invented by Roger Bacon. It was described in the early part of the sixteenth century by Leonardo da Vinci when he told how images of outside objects are formed in darkened rooms by a small circular hole in the shutter. About the middle of the same century Cardan improved the camera obscura by placing a double convex lens in the opening.

If we compare Fig. 498 with the diagram of the eye, we find that the photographic camera is modeled after the eye. The sensitive screen corresponds to the retina and receives the image. The lens or combination of lenses acts like the crystalline lens of the eye. It forms upon the sensitive plate a real, inverted image, smaller than the object. The diaphragm, or stop, regulates the amount of light which can enter the camera just as the iris permits the proper amount of light to enter the eye through the pupil. The shutter excludes light just as the eyelids do. The interior of the camera is blackened to absorb stray rays of light.

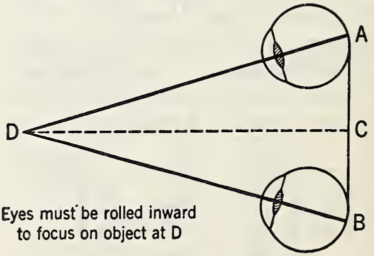


Fig. 497. How we use two eyes to estimate distance.

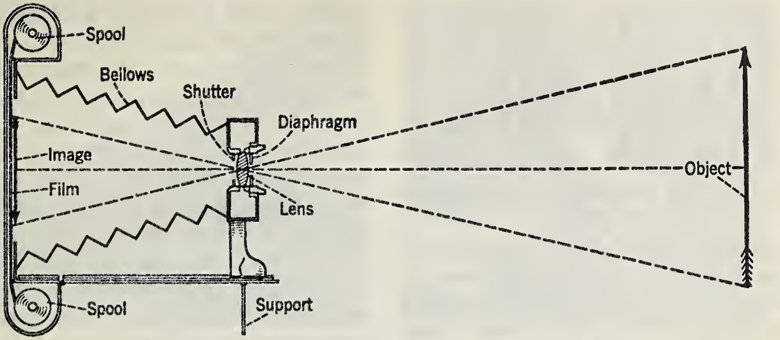


FIG. 498. Diagram to show how a camera forms images.

**462. Eye versus camera.** In several ways the eye is decidedly superior to the camera. The eye is self-focusing, while in the camera the lens must be moved nearer to the sensitive plate or farther away, depending entirely upon the distance of the object. For this reason, the side walls of the camera are collapsible. The iris automatically regulates the amount of light the eye needs for forming clear images. The operator needs considerable experience to adjust the diaphragm of a camera properly for different light intensities. With the eye we get distance and perspective; the photograph formed by the camera does not have perspective.

On the other hand, the camera has some advantages over the eye. It gives us a picture of all the details of the object, while some of the details of an image formed on the retina are so feebly impressed that they are either ignored or quickly forgotten. The photograph gives us a picture of an object at a certain instant in a given position, while the image received through the eye may be a *composite* picture of several successive images in different positions. Each image persists for about $\frac{1}{16}$ second before another that is distinct from the first may be formed. Thus we remember a composite picture, possibly formed by the blending of several images. For this reason, two truthful persons may be almost contradictory in describing an accident both have witnessed. In one of the Olympic games, the judges awarded a runner fifth place. The motion pictures later showed unquestionably that he finished in second place. Motion pictures of football games show the coach clearly what each player did during the game.

**463. What are optical illusions and camouflage?** The expression "You cannot fool me, I saw it" is so common that one might infer that the eye is infallible. Yet we pay a magician to fool the eye. Often the image which the eye forms is influenced by former experiences which we have had. When our judgment based upon such experiences is at fault, then optical illusions occur. (See Fig. 499.) Do the lines appear to be parallel? There are many similar illusions of direction. (See Figs. 500 and 501.) A brown log or stump in the darkening twilight may appear to the observer as a dog or other animal when his imagination modifies the image on the retina.

Many insects are very hard to see

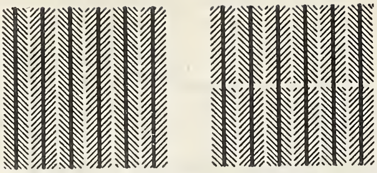


FIG. 499. Do the heavy lines seem straight and parallel?

when at rest on twigs or leaves because they assume the same color as their surroundings. This protective coloration is common among animals that change a brown or tawny coat of summer for one of white in winter. Many fishes change their colors and take the color of their surroundings. The white stripes and patches of the tiger, zebra, and giraffe resemble spots or streaks of sunlight passing through foliage or reflected by leaves.

The art of mimicry and protective resemblance is much practiced in wars on land and sea. Battleships are painted gray to produce low visibility. They blend with the horizon colors and are hard to see. Paint is much used to give an object the appearance of its surroundings. Fig. 502 shows two of the methods used in military work to obscure some military movements. By similar methods of *camouflage* many ships escape from enemy submarines.

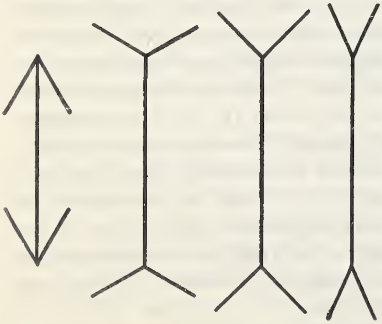


FIG. 500. Which vertical line is longest?

**★464. What uses have anastigmat and rectilinear lenses?** When ordinary lenses are used with the diaphragm well opened, the image produced is generally sharp and well defined at the center, but it is "streaky" or blurred near the edges. This defect of lenses is known as astigmatism. By using a combination of lenses of suitable refractive indexes and focal lengths, like that shown in Fig. 503, it is possible to make an *anastigmat* lens which gives good definition over a wide area. At the same time, the lens combination must be corrected for spherical and chromatic aberration. (See Section 494.)

Lenses that can be used with a large aperture are fast, and they can be used for high-speed work. The *effective aperture* of a lens is equal to the diameter of the lens as it appears when seen through the front lens. The speed of a lens depends upon the ratio of its effective aperture to its focal length, or upon its *relative aperture*. In an $F$-4 lens, the focal length is 4 times the effective aperture. Such a lens is 4 times as fast as an $F$-8 lens, and 16 times as fast as an $F$-16 lens. The speed ratios are proportional to the squares of the relative apertures.

If a plano-convex lens is placed in a camera so the flat side is toward the object, the image that is formed is dis-

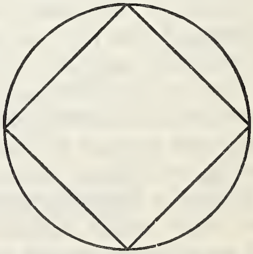
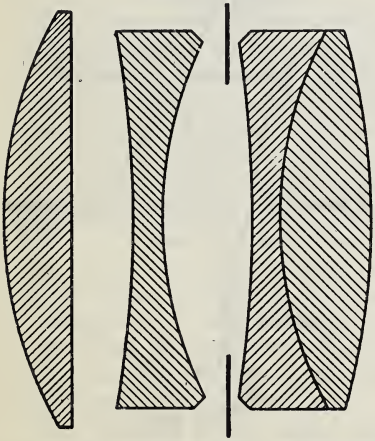


FIG. 501. Observe how the square makes the circle appear flattened.

*Pictures, Inc.*

Fig. 502. The art of camouflage is an old one. From Shakespeare's tragedy *Macbeth* we read that Birnam Wood traveled to Dunsinane. As one looks at these pictures, he may suspect that that particular phenomenon is being repeated.

torted so that a square has the appearance shown by the solid lines of Fig. 504*A*. When the lens is turned so that its convex side faces the object, the opposite effect is produced. (See Fig. 504*B*.) Distortion is produced by all single lenses, the effect being especially noticeable in pictures of buildings with straight lines. The defect may be remedied by using two lenses with their corresponding curves facing in opposite directions and with the diaphragm between the lenses. Such a combination is called a *rectilinear* (straight-line) lens.



*Courtesy of Bausch and Lomb Optical Company*

Fig. 503. Anastigmatic lenses.

**465. What is meant by a simple magnifier?** Everyone has used a simple magnifier to produce an enlarged image of an object that is near the eye. We have learned that the *apparent* size of an object increases as it is brought nearer to the eye, because the visual angle is enlarged. We found, too, that the eye does not form a clear image of an object that is brought nearer the eye than 10 in., or 25 cm. Since the muscles of the eye cannot make the lens more convex, we may use a convex lens to assist the eye in forming clear images of objects closer than 10 inches.

A double convex lens of rather short

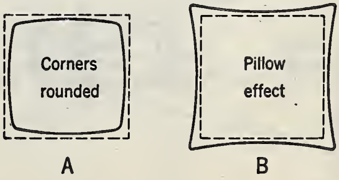


Fig. 504. How the diaphragm in a camera affects straight lines.

focal length is generally used as a simple magnifier. This lens is held a little nearer to the object than its focal length and the eye is placed close to the lens. This is a practical example of Case 6, and the image formed is enlarged, virtual, and erect. To represent the magnifier graphically we merely draw a diagram to show how an image is formed when the object is nearer the lens than its principal focus, and place the eye on the opposite side near the lens. (See Fig. 505.) Since the object is very near the principal focus, the *approximate* magnifying power of a simple magnifier equals

$$\frac{\text{the least distance for distinct vision}}{\text{focal length of the lens}}$$

For example, we divide 25 cm. by the focal length in cm., or 10 in. by the focal length in inches. To magnify 5 diameters, we use a lens of 5-cm. focal length.

**466. How is the compound microscope constructed?** The invention of the compound microscope by Janssen marked the beginning of a new era in the study of plant and animal physiology. Without the microscope, nothing would now be known concerning the action of bacteria in producing diseases. By its use, Louis Pasteur learned why foods spoil and how certain diseases are caused. If it were not for the serums and antitoxins which his work made possible, at least one in eight of our readers would have died in infancy.

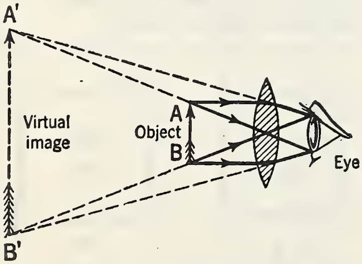


Fig. 505. How the simple magnifier forms images.

From our study of lenses, it seems as if we ought to be able to form an enlarged image by means of one lens and then magnify this image by the use of another lens. That is exactly what the *compound* microscope does. Since the image to be magnified must be a *real* image, we make use of Case 4 to form the first image, and of Case 6 to magnify this image. The two convex lenses are mounted at opposite ends of a brass tube whose length is adjustable. The lens near the object is called the *objective*, and the one near the eye is called the *eyepiece.*

In Fig. 506 we use a converging lens as the *objective*, and the object, *AB*, is placed a trifle farther from this lens than its focal length. At *A′B′*, a distance slightly more than twice the focal length of the objective lens, we have

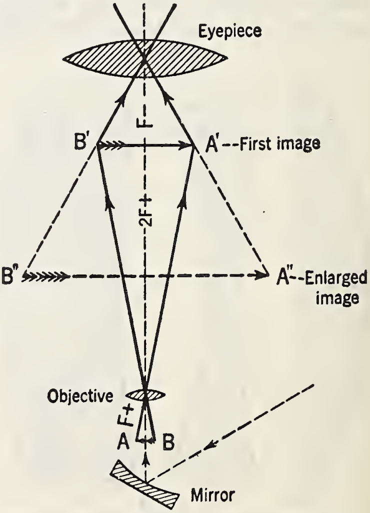


Fig. 506. The compound microscope forms an image and then magnifies that image.

formed an enlarged, real, inverted image. This image is enlarged by the *eyepiece* which acts as a simple magnifier. The mirror is used to reflect strong light upon the object. Since the light is spread out over a greater surface when we form an enlarged image such an image will become fainter and fainter as we increase its magnification.

The magnifying power of the objective is approximately equal to the length of the tube $L$, divided by the focal length, $F$, of the objective, or $\frac{L}{F}$. The magnifying power of the eyepiece equals $\frac{25}{f}$ (cm.). The total magnification is equal to the product of the two, or $\frac{25L}{fF}$, if the measurements are all given in centimeters.

Suppose that the tube of a microscope is 16 cm. long, the focal length of the objective is 0.5 cm., and the focal length of the eyepiece is 2.5 cm. The objective magnifies the object 32 diameters, and the eyepiece magnifies it 10 diameters. The total magnification is 320 diameters.

★**467. There are two kinds of astronomical telescopes.** Such telescopes are of two kinds: *refracting* and *reflecting.* Like the compound microscope, the refracting telescope has two lens combinations. The *objective* lens is of large diameter to enable it to collect large quantities of light. Of course, the object to be viewed is distant from the objective lens *more than twice* its focal length. Hence, the image that it forms is smaller than the object, but exceedingly bright. (See Fig. 507.) The eyepiece magnifies the real image which is produced by the objective lens.

The objective of the Yerkes *astronomical* telescope has a diameter of 40 in. and a focal length of more than 60 ft. Such an objective forms a real image of distant heavenly bodies, which is so bright that it can be highly magnified by the eyepiece. When an eyepiece whose focal length is 0.25 in. is used, this telescope magnifies almost 3000 diameters. The magnifying power is approximately equal to the focal length, $F$, of the objective divided by the focal length, $f$, of the eyepiece, or $\frac{F}{f}$. (See Fig. 508.)

The *reflecting telescope* uses a large concave mirror instead of an objective lens for collecting light waves. The real image formed by such a mirror is then magnified by the eyepiece. Figures 509 and 510 show the mold and the large disc of glass for making a huge 200-inch diameter reflector. When finished and mounted, it is expected to bring heavenly bodies to a distance only one-fourth that ever before attained by a telescope. The Mt. Wilson telescope, whose mirror is 100 in. in diameter, is shown in Fig. 511. We need to remember that 100 in. is more than 8 ft.

The image formed by astronomical telescopes and by microscopes is inverted and reversed. (See Fig. 507.) The user of a microscope soon becomes accustomed to this condition, and it makes little difference to astronomers whether they see the sun, moon, or planets erect or inverted.

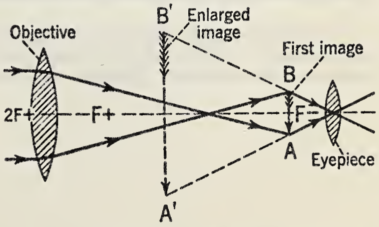
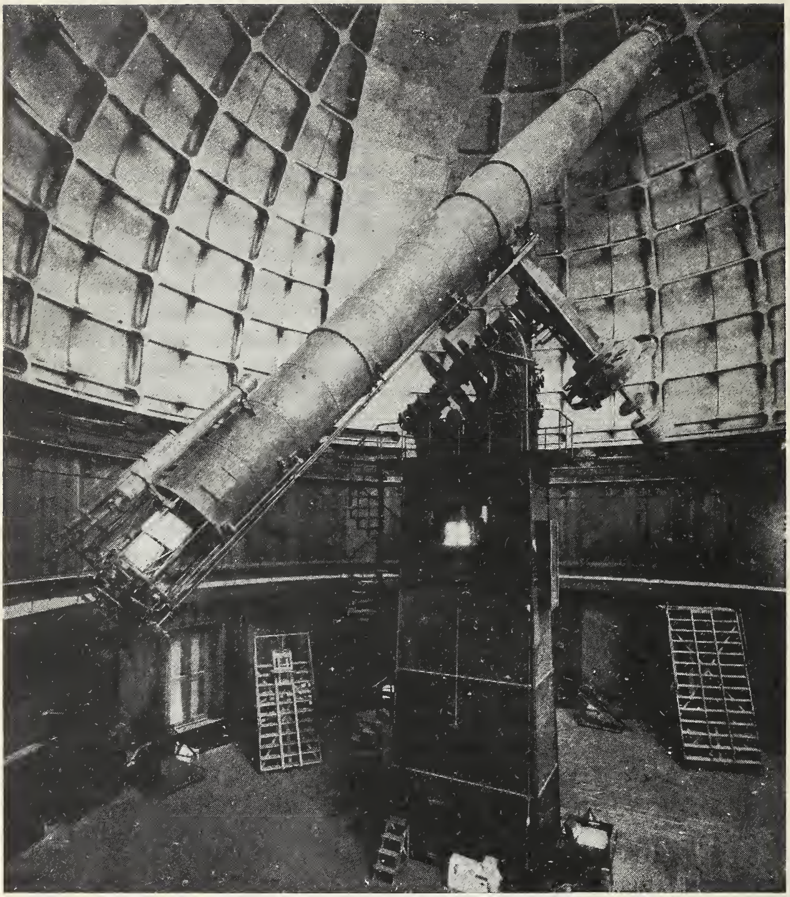


Fig. 507. Diagram to show how a refracting telescope forms images.



*Courtesy of the Lick Observatory*

Fig. 508. The Lick telescope and observatory. The telescope and counterpoises (21 tons) are moved by electric motors and controlled by a clock which can keep the telescope pointed at any astronomical body. The floor may be raised or lowered to meet the needs of the observer.

# THE SUBTRACTIVE COLOR PROCESS

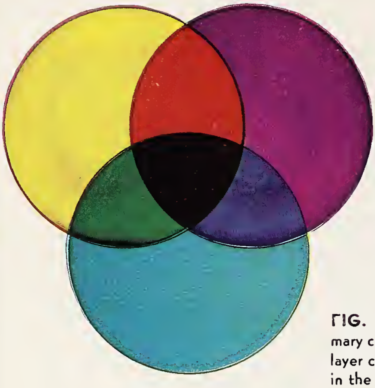
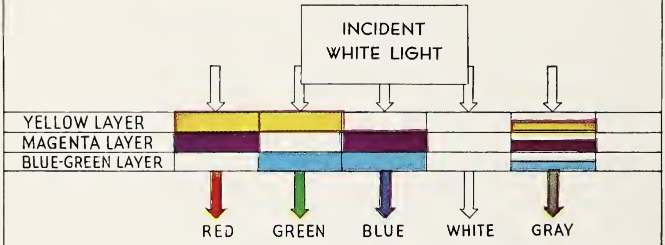


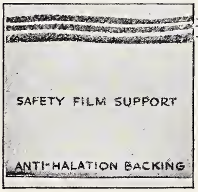
**FIG. 1,** illustrating the principle of color formation in the subtractive process. Each circle is printed in one of the three minus colors, so that each absorbs one of the three primaries (red, green or blue). Where any two overlap, two primaries are subtracted, so that one only remains; where all three overlap, black results.

**FIG. 2,** illustrating the formation of primary colors, of white and of gray, in a multilayer color film by superimposed dye images in the three layers.


INCIDENT
WHITE LIGHT
YELLOW LAYER
MAGENTA LAYER
BLUE-GREEN LAYER
RED
GREEN
BLUE
WHITE
GRAY

# THE KODACHROME PROCESS

**FIG. 3.** A cross-section of Kodachrome Film, showing the extreme thinness of the three differently color-sensitized coatings, separated by plain gelatin layers.


SAFETY FILM SUPPORT
ANTI-HALATION BACKING

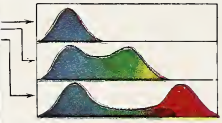


**FIG. 4,** indicating the color sensitivities of the three component emulsion layers.

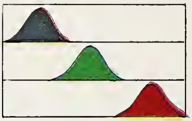
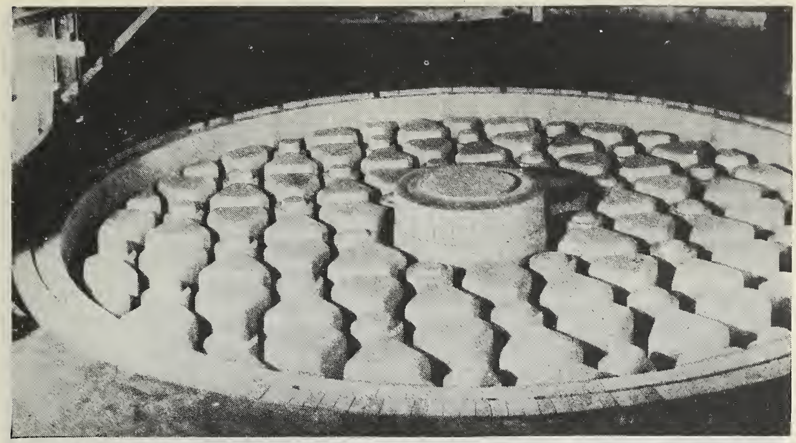


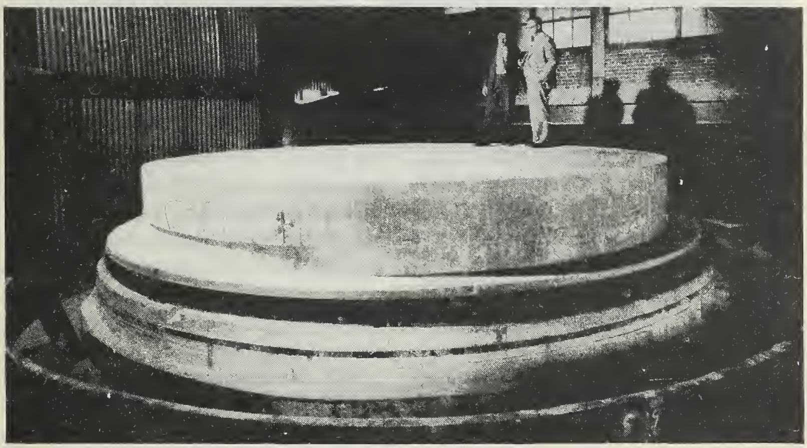
**FIG. 5,** showing the effective color separation obtained in these three layers.

*Courtesy of Eastman Kodak Company and The Macmillan Company*



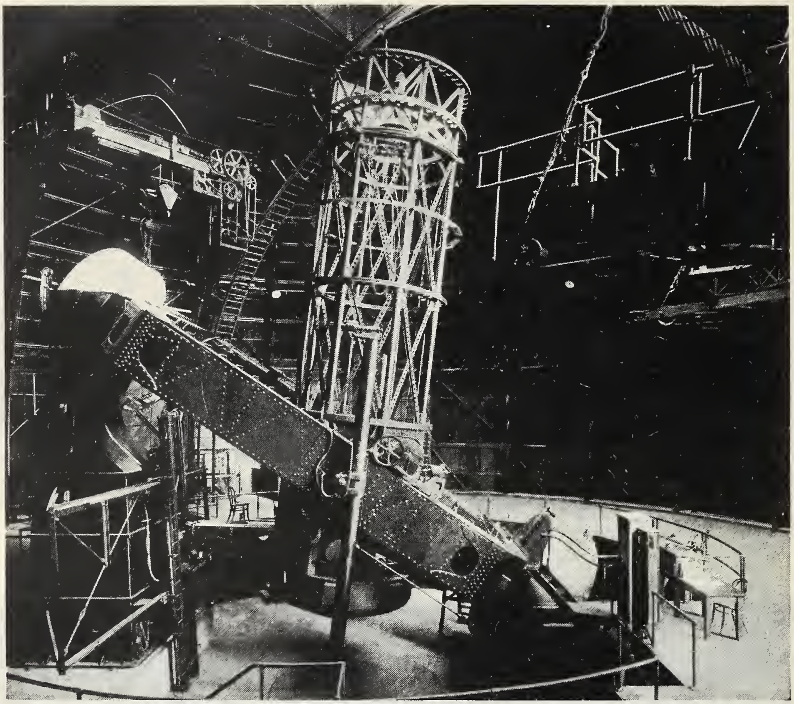
*Courtesy of the Corning Glass Company*

Fig. 509. The mold for receiving the molten glass used to make the 200-inch disc for the world's largest telescope. The central core will produce a 40-inch hole used for mounting the large reflector disc.



*Courtesy of the Corning Glass Company*

Fig. 510. This large disc of glass was made at Corning, New York, for use in the large telescope for the California Institute of Technology. It is 200 inches in diameter and more than two feet thick. It weighs 20 tons. When completed, it should bring heavenly bodies to a distance of not more than one-fourth that attained by the use of any other telescope.



*Courtesy of Mount Wilson Observatory*

FIG. 511. The Mount Wilson reflecting telescope has a reflector 100 inches in diameter.

**★468. How is the terrestrial telescope constructed?** In the ordinary field telescope, the objective lens and the eyepiece form images just as they do in an astronomical refracting telescope. With this instrument, however, it would be very awkward to see objects inverted. For that reason, another lens system, as seen in Fig. 512, is used to reinvert the real image formed by the objective so that we may see it erect. Of course, it must be placed at exactly twice its own focal length from the image formed by the objective.

Telescopic sights are sometimes used on long range rifles. Cross-threads intersecting at right angles are suspended in the telescope. When the telescope is adjusted so that the image is focused on the intersection of these threads, then the object, the center of the objective, and the point of intersection are all in the same straight line. Surveyors use the same kind of telescope in their transit instruments and levels.

**469. How are opera glasses constructed?** The opera glass is lighter than the telescope, and, having two tubes, it has the advantage of giving binocular vision.

The eyepiece has the same focal length as the crystalline lens of the eye, but it is concave; hence it practically neutralizes the lens of the eye. The objective, a lens of larger size and greater focal length, is then virtually substi-

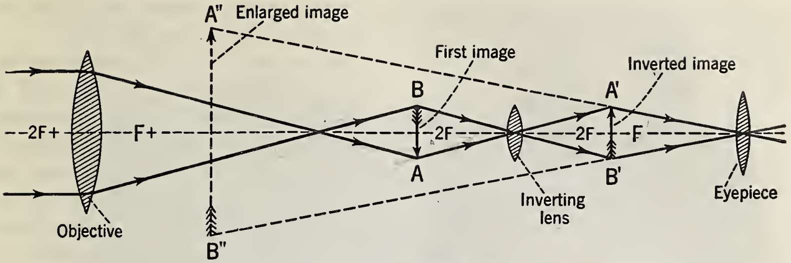


FIG. 512. The field telescope.

tuted for the crystalline lens. Opera glasses usually magnify only 3 or 4 times, the magnifying power being approximately equal to the length of the tube in inches. The image *appears* erect, since it is formed on the retina just as images formed by the lens of the eye. In Fig. 513, the effect of the double concave lens used as the eyepiece is shown as it partially nullifies the effect of the crystalline lens of the eye.

Some binoculars are made with total reflecting prisms, like those of Fig. 514. Such an arrangement permits the lenses to be set farther apart to increase the visual angle. Thus the observer can scan a wider field without changing his position.

**470. How does the optical lantern or the projector form images?** This optical instrument is an important part of the equipment of nearly every school. It is extensively used to throw an enlarged image of a transparent slide upon a screen. By the addition of reflecting mirrors, some instruments of this type are used to project images of opaque objects. The objective lens is a combination of converging lenses which act as a single lens. The slide is placed a trifle farther from the lens than one focal length. The screen used to receive the image is distant considerably more than twice the focal length of the objective. Since the image is real, inverted, and enlarged, the slide must be placed upside down in the holder so that it will appear erect on the screen.

The image is greatly enlarged in such projection, and it will be very faint unless the slide is *very strongly illuminated.* A very high-candle-power lamp is used, usually 500 C.P. or more. A concave mirror, also shown in the diagram, is placed behind the lamp to focus more light rays upon the slide. Still more important for strong illumination are two large diameter (5 or 6 in.) plano-convex lenses called condensers. The condensers are placed just about their focal length directly in front of the lamp, and a trifle less than their focal length from the slide itself. (See Fig. 515.)

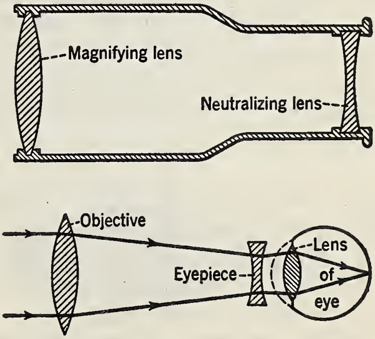
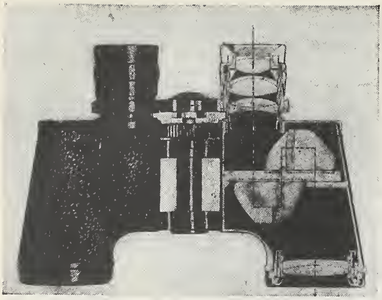


FIG. 513. Opera glasses. How they form images.



*Courtesy of Bausch and Lomb Optical Company*

Fig. 514. Binoculars generally have total reflecting prisms.

**471. What principle makes motion pictures possible?** The spokes of a rapidly rotating carriage wheel succeed one another so rapidly that the wheel appears solid. This happens because the image of an object formed on the retina of the eye persists for from $\frac{1}{20}$ to $\frac{1}{16}$ of a second after the object causing the image has been removed. The wheel appears solid, then, because the image of a second spoke is formed on the retina before the image of the first spoke has faded out. This principle of *duration of vision* makes possible the showing of motion pictures.

In preparing the film, from 20 to 50 exposures of a moving object are made per second. When the pictures are thrown upon a screen, they succeed one another at about the same rate as that at which they were taken, thus giving the effect of continuous motion. A slow or fast motion effect can be gained by varying the speed.

We observe that each picture on the strip of film shown in Fig. 516 is slightly different from the preceding one. Film made from nitro-cellulose is so flammable that both the projector and the film must be enclosed in a fireproof booth when it is used. More and more a so-called safety film made of cellulose acetate is being used in place of the more flammable nitro-cellulose film. It is particularly desirable for home and school use.

Certain optical illusions are noticed in viewing motion pictures. If an airplane propeller is started slowly by hand it appears to be turning backward. The successive appearances of the propeller blades are slower than the succession of pictures on the screen. Occasionally one sees on the same film an automobile or other vehicle in which the wheels appear to be turning backward, another vehicle in which the wheels seem to be turning forward in the proper direction, and still others in which the wheels appear to be standing still as the vehicle moves forward. These phenomena depend upon the speed at which the spokes succeed one another compared with the rate at which successive pictures are thrown upon the screen.

**472. How are motion pictures projected?** The motion picture projector,

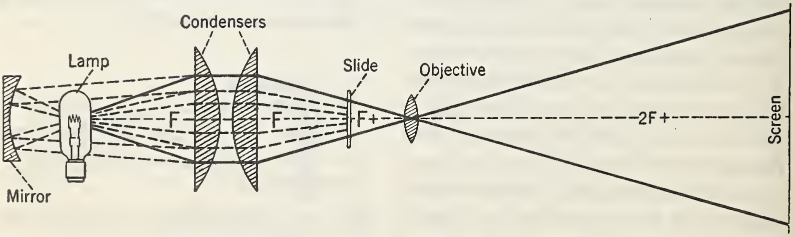
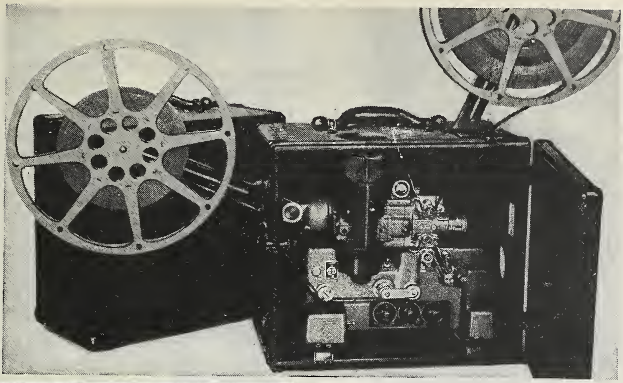


Fig. 515. How the optical lantern forms images.



*Courtesy of Bell and Howell*

FIG. 517. A portable motion picture projector, small enough to carry in a case. The film is drawn from the reel at the right, down through sprockets behind the objective, and back to the reel at the left.

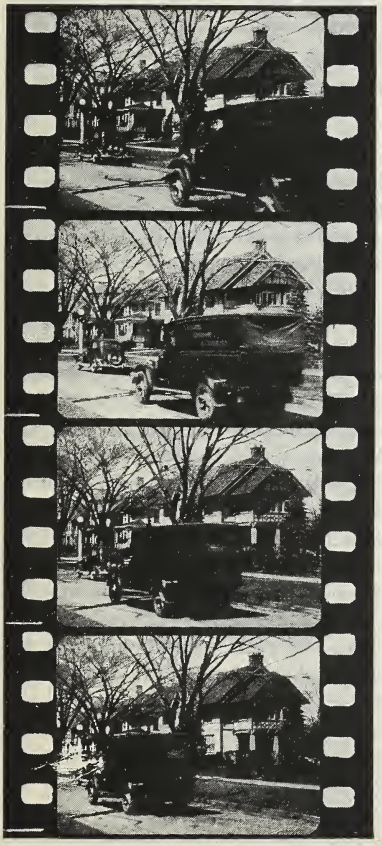


FIG. 516. A strip of motion picture film. Each picture is slightly different.

Fig. 517, does not differ from the optical lantern in the manner in which images are thrown upon the screen. The image is formed by the objective in the same manner, and condensers are used to concentrate a large amount of light upon the film, which takes the place of the stationary lantern slide. The mechanism for operating the film is somewhat complex. An electric motor is used to wind the film upon one reel as it is unwound from another. Each picture must come to a complete stop while it is being shown. Then it moves on and another picture is substituted for it before the image of the first one has faded out from the retina. To prevent streaks, a revolving shutter covers the picture while the film is actually moving. This makes it an interesting question, then, whether we ever see motion pictures.

**★473. How is sound added to motion pictures?** It is possible to have the speech and music recorded electrically

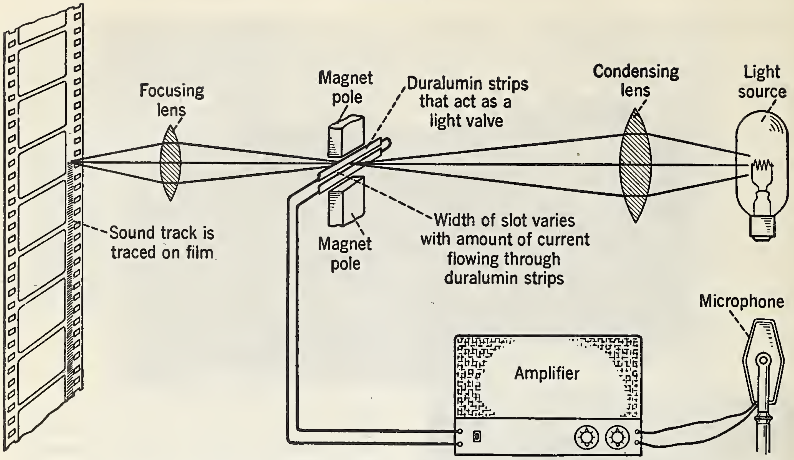

Focusing lens
Magnet pole
Duralumin strips that act as a light valve
Condensing lens
Light source
Sound track is traced on film
Magnet pole
Width of slot varies with amount of current flowing through duralumin strips
Microphone
Amplifier

Fig. 518. A light valve used in adding sound recording to a picture film.

on a phonograph disc and then reproduced as the film is shown. With such an arrangement, both the phonograph and the motion picture projector are driven by the same motor in order to make the timing perfect.

In nearly all cases, the sound is recorded on the film itself as a narrow strip near the margin of the film. One of the methods used is as follows.

1. A microphone which is free from distortion is used to change the sound waves into electrical currents.

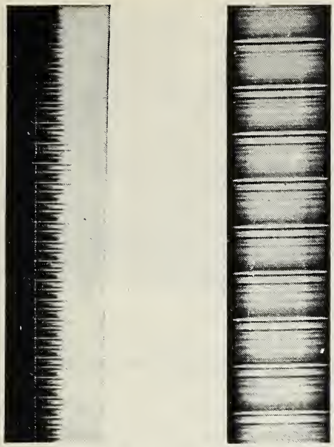
2. The corresponding electrical currents are then amplified and passed through a *light valve.* (See Fig. 518.)

3. The light valve consists of thin light strips of the metal duralumin placed about 0.001 in. apart between the poles of a powerful magnet. As the amplified current flows through these light metal strips in succession, they are attracted and repelled by the poles of the magnet so that the width of the slit between them varies in proportion to the strength of the current produced by the sound waves.

4. A beam of light passes through the narrow slit of the light valve and is focused upon the edge of the film. The variations in the width of the slit cause variations in the amount of light passing through the valve. When the film is developed it will have light and dark bands which correspond to the sound waves that entered the microphone. Fig. 519 shows the sound waves on a separate film and in Fig. 520 they are shown on the picture film itself.

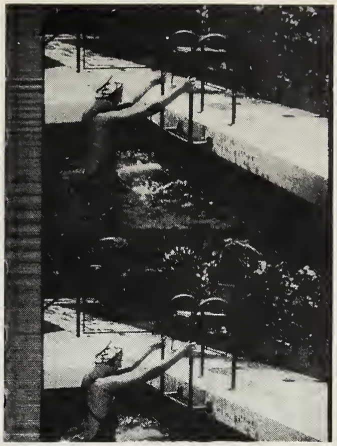
In reproducing such a sound film, a beam of light passes through the sound track on the edge of the film and then through a narrow slit to a *photo-electric cell,* or electrical eye. (See Section 681.) The variations in the light falling upon such a cell cause corresponding variations in the electrical current which the cell produces. The variable electric currents are amplified and then conducted to a loud speaker, which converts the electric currents back into sound waves. (See Fig. 521.)

**474. How are lampshades used to modify illumination?** Daylight is usu-



*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 519. The vibration waves of a sound film.



*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 520. Sound film recorded along the edge of a picture film.

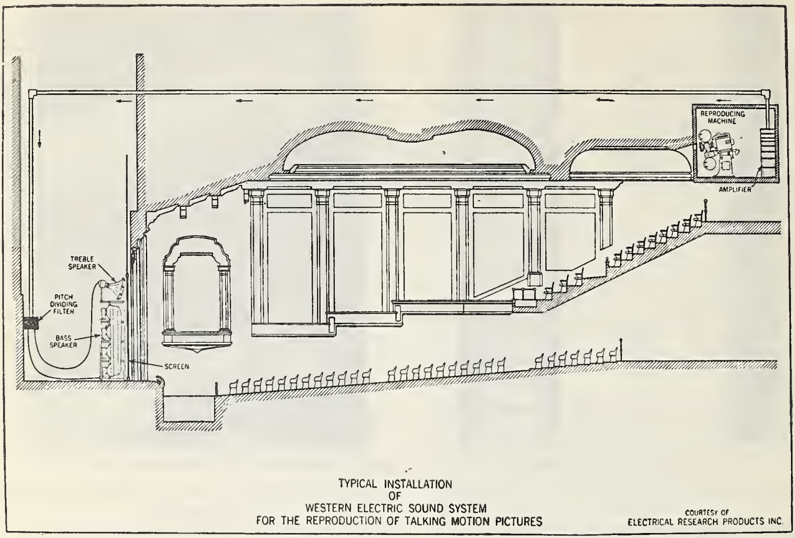
ally well diffused, but for the proper distribution of artificial light, shades or reflectors are essential. In a library or reading room the light should be fairly close and concentrated. For living rooms and assembly halls, the illumination is more general.

In the *direct* system of illumination, the light shines directly upon the object to be lighted; a rather narrow shade or a concave reflector may be used to concentrate more light upon the object. This is the most economical system of lighting, but the eyes are sometimes injured by the glare which comes from the light itself or from the reflector. In electric lighting, the bulbs are either frosted or made of translucent glass in order to modify the glaring light of the filament. (See Fig. 462.)

For general illumination, the *indirect* or the *semi-indirect* system is often used. With the indirect system the lamps are placed near the ceiling; a large, opaque, bowl-shaped reflector placed beneath the lamp reflects the light to the ceiling, whence it is diffused to all parts of the room. (See Fig. 522.) If the ceilings are white, an even diffusion of the light is thus secured and the system is fairly efficient. White or light yellow walls and ceilings may reflect as much as 50% of the light they receive. Red, brown, or green walls absorb about 85 or 90% of the light received, and reflect only 10 to 15%; hence they are not suitable for use with indirect lighting. While the indirect system of lighting is always more costly, yet the light is soft and pleasing, and sharp shadows are eliminated.

In the *semi-indirect* system of lighting, the lamp is partially enclosed by a translucent shade or globe. (See Fig. 523.) A part of the light is directed to the ceiling and then reflected to the floor or walls, and a part of it diffuses through the translucent globe directly to the user. It combines the advantages of the direct and indirect systems.

*Diffusion* lighting is much used for


REPRODUCING MACHINE
AMPLIFIER
TREBLE SPEAKER
PITCH DIVIDING FILTER
BASS SPEAKER
SCREEN
TYPICAL INSTALLATION
OF
WESTERN ELECTRIC SOUND SYSTEM
FOR THE REPRODUCTION OF TALKING MOTION PICTURES
COURTESY OF
ELECTRICAL RESEARCH PRODUCTS INC.

*Courtesy of the Western Electric Company*

Fig. 521. This diagram shows how a theater may be fitted for showing sound-motion pictures.

hallways and kitchens. In such a system, a translucent globe nearly or entirely encircles the lamp. (See Fig. 524.)

Some floor lamps are now being made which have several switches. They can be used for direct lighting, or for a combination of indirect and semi-indirect lighting. (See Fig. 525.)

At one time, it was common practice to outline the domes and towers of large buildings with rows of incandescent lamps. The method has been superseded by the use of *floodlighting.* Fig. 526 shows the Woolworth Building floodlighted, and Fig. 527 a battery of projectors used for the purpose. Niagara Falls is floodlighted at night, and different colors are used to enhance its beauty. Athletic fields are often lighted for games played at night.

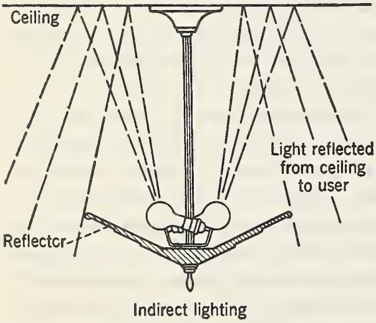

Ceiling
Light reflected from ceiling to user
Reflector
Indirect lighting

Fig. 522. Indirect lighting gives soft light effects, but it is not very efficient.

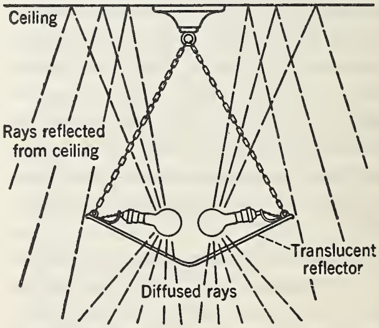
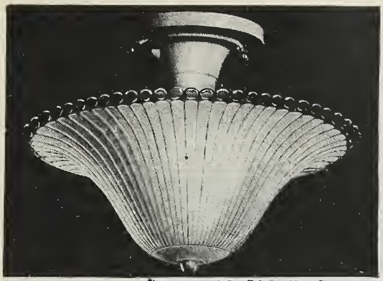

Ceiling
Rays reflected from ceiling
Translucent reflector
Diffused rays

Fig. 523. Efficiency is increased by using semi-indirect lighting.



*Courtesy of the Lightolier Company*

FIG. 524. Diffusion lighting finds use in hallways, kitchens, and bathrooms.

Night baseball and football are very popular in some cities. (See Fig. 528.)

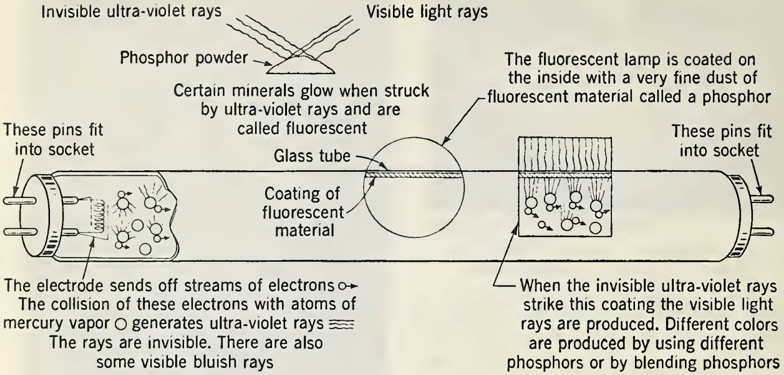
The fluorescent lamp, which was widely used for lighting the World's Fair in New York, is rapidly coming into use in stores and factories, and in halls and kitchens of the home itself. Its operating cost is probably less than 40% of that of the same candle power tungsten lamp. The fluorescent lamp consists of a tube from one to one and one half inches in diameter and from 18 to 36 inches in length, fitted by pins into a special socket. The inner walls of the tube are coated with chemicals known as *phosphors*. When exposed to ultraviolet light, these phosphors glow and yield such colors as gold, red, blue, pink, and green. By

*Courtesy of the Lightolier Company*

FIG. 525. Several variations in lighting effects are possible with lamps of this type.

*Courtesy of the Woolco Realty Corporation*

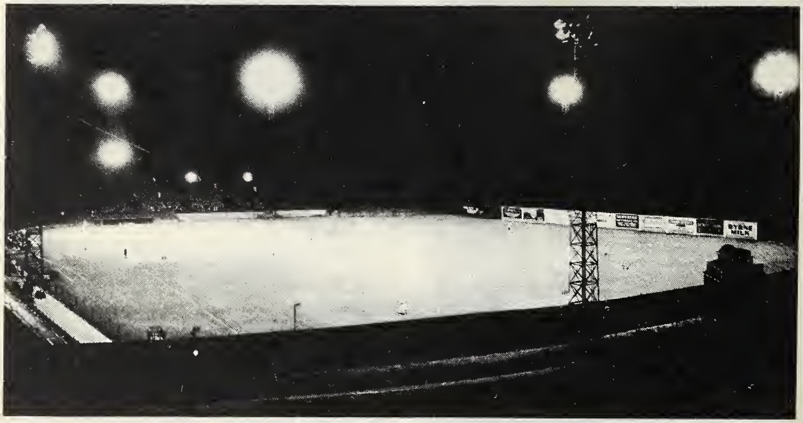
FIG. 526. The tower of the Woolworth Building as it appears when floodlighted.



Invisible ultra-violet rays
Visible light rays
Phosphor powder
Certain minerals glow when struck by ultra-violet rays and are called fluorescent
The fluorescent lamp is coated on the inside with a very fine dust of fluorescent material called a phosphor
These pins fit into socket
Glass tube
Coating of fluorescent material
These pins fit into socket
The electrode sends off streams of electrons
The collision of these electrons with atoms of mercury vapor generates ultra-violet rays
The rays are invisible. There are also some visible bluish rays
When the invisible ultra-violet rays strike this coating the visible light rays are produced. Different colors are produced by using different phosphors or by blending phosphors

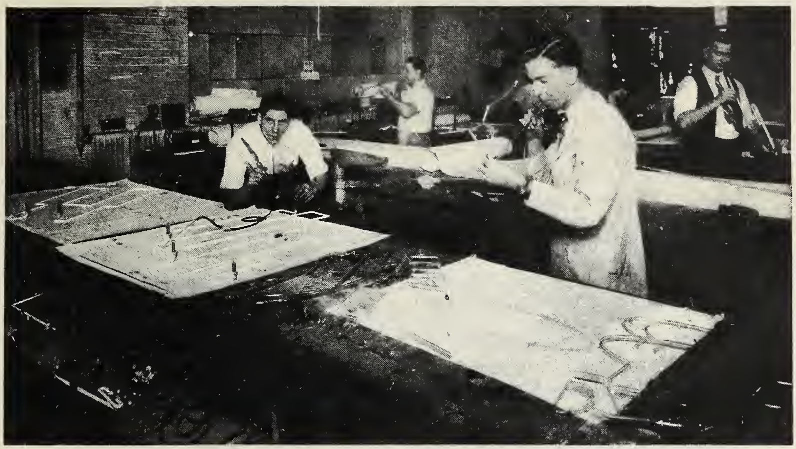
*Courtesy of the Westinghouse Electric and Manufacturing Co.*

FIG. 527. This figure shows the manner in which fluorescent lamps are constructed. The installation cost of fluorescent lamps is greater than that of tungsten lamps, but it costs less to operate them.



*Courtesy of the Crouse-Hinds Company*

FIG. 528. Huge projectors are used to illuminate an athletic field for night baseball or football.



*Courtesy of Claude Neon Lights, Inc.*

FIG. 529. Making neon tubes for advertising signs.

blending several phosphors, a fine white light may be produced. The ultraviolet rays are produced when electrons which are emitted by the hot electrodes bombard atoms of mercury vapor which are enclosed within the tube. A starting device must be used to make the electrodes heat up quickly and start the flow of electrons through the tube. (See Fig. 527.)

**475 How is neon used in lighting?** The use of glass tubes containing neon gas is very common for advertising signs or displays. It is possible to bend glass tubing into any desired shape to form letters or designs. The tube is then exhausted and filled with the gas neon under reduced air pressure. Electrodes sealed in the ends of the tube are used for making electric contacts. When the current is turned on, the whole tube is filled with a yellowish-orange or reddish-orange light. If argon gas and mercury vapor are mixed with the neon, a blue light can be produced. It is possible, too, to produce other colors by the use of colored glass for the tubes. Neon lighting is popular, because its effects are beautiful and striking, and also because the cost of operation is so low that small signs need not be turned off. (See Fig. 529.)

## Summary

The eye is the most commonly used optical instrument. It has a lens which forms real, inverted images on the retina. Certain defects of the eye, such as nearsightedness, farsightedness, and astigmatism, can be corrected by means of glasses, or spectacles.

By focusing both eyes upon an object, we learn to judge distance, provided we know the size of an object. If we know the distance, we can judge size fairly well.

The camera is patterned after the eye itself. In some respects it is more accurate and efficient than the eye. In other respects the eye is superior. The camera forms real images upon a sensitive film or plate by means of a lens system. Such an image is real, inverted, and usually smaller than the object.

The compound microscope forms first an enlarged, inverted, real image, as in Case 4, and then magnifies the image by means of an eyepiece used as a simple magnifier, which is an application of Case 6.

In the telescope, either a large lens or a concave mirror is used to collect large quantities of light to form a bright, real image of a distant object. The image is then magnified by means of a powerful eyepiece.

The optical lantern uses condensing lenses to gather many rays of light and focus them upon a transparent slide whose image is to be thrown upon a screen by a lens system which utilizes the principle of Case 4. The motion picture machine projects images in a similar manner, but the images succeed one another in such rapid succession that the effect is continuous. They utilize the principle of duration of vision.

Lenses and mirrors are much used in our homes, streets, and recreation fields to focus light where we wish it to give the desired illumination.

*How many of the following terms and phrases can you define or explain?*

The eye
Nearsightedness
Farsightedness
Astigmatism
Camera *versus* eye
Astronomical telescope
Opera glasses
Duration of vision
Neon lighting
How eye forms images
Judging size and distance
Optical illusions
Compound microscope
Magnifier
Optical lantern
Motion pictures
Sound motion pictures
Lampshades and illumination

## QUESTIONS

1. Why is the image formed by a compound microscope inverted?
2. Why is the interior of optical instruments painted black?
3. In old age the lens of the eye loses the power of accommodation. What kind of glasses do old persons use for reading?
4. Convexo-concave or concavo-convex lenses (meniscus) are now more often used in spectacles than the flat lenses. What advantages do such meniscus lenses have?
5. Where is the slide placed in an optical lantern with respect to the focal length of the objective?
6. What advantages has the eye over the camera as an optical instrument? What are its disadvantages?
7. Ask each one of a group of 10 or 12 persons how large the full moon seems to him when at the zenith. Why do the answers vary so much?
8. Why does the full moon appear so much larger when it is just rising than it does when it is on the meridian?
9. How is it that owls and cats can see so well at night? What shape has the pupil of a cat's eye when seen at night? When observed in daylight?
10. Name several optical instruments which you have used that form real images. Name several that form virtual images.
11. Why do the parallel rails of a railroad track appear to meet at a distance?
12. Draw a diagram to show where a light must be placed with reference to a large double convex lens to produce a spotlight? Where is the light placed with reference to the lens in a lighthouse?
13. In what respects is a photograph of an accident better than the testimony of an eyewitness? In what ways is the testimony superior?

14. Some states refuse to issue registration licenses for cars unless the headlights are properly focused. Look up the method of focusing such headlights and be prepared to report to class.

15. What is meant by binocular vision? What are its advantages?

16. Red glass reflectors placed upon the rear of automobiles are required by law in some states. Explain.

17. What is meant by the saying: "The hand is quicker than the eye"?

18. Why do some persons permit their neon signs to remain lighted in the daytime?

## PROBLEMS

### Group A

1. A lead pencil 6 in. long when held 12 in. from the eye appears as tall as a tree 100 ft. away. How high is the tree?

2. A reading glass has a focal length of 5 in. What is its magnifying power?

3. The tube of a microscope is 180 mm. long. What is its magnifying power when the eyepiece has a focal length of 2 cm., and the objective has a focal length of 3 mm.?

4. The lens combination of a compound microscope magnifies an object 800 diameters. How many times as large does the cross-sectional area appear as the object which is being examined?

### Group B

5. A camera has a lens whose focal length is 6 in. If the plate is 6.25 in. from the lens when the camera is in focus, how far away is the object? Suppose that the object is 6 ft. high by 8 ft. wide, what is the smallest sized plate that can be used to show all of the object at the distance found?

6. If a film is one and one-eighth inches wide, what are the relative distances of the screen and the film from the lens if the image just fills a screen 9 ft. wide? If a theater is 64 ft. long, what is the actual distance between lens and film when the picture is in focus? Calculate the focal length of the lens that will be needed.

7. A picture 8 ft. high by 12 ft. long hangs on one wall of a room. A photographer, who wishes to take a photograph of this picture, places a camera which has a focal length of 12 in. just 13 ft. from the picture. How far distant from the lens will the image be formed? What size plate must the photographer use to include the entire picture?

8. A photograph is being taken of a building which is just 100 ft. distant. The plate upon which the exposure is being made is exactly 1 ft. from the lens. Calculate the focal length of the lens. If the picture just covers a plate that is 6 in. high by 8 in. long, what is the height and length of the building?

# *Light — Color*

**476. How is light dispersed?** Cut-glass dishes and pendants from candlesticks give a beautiful display of colors when the sun shines upon them. Let us take a glass prism and permit a beam of sunlight to fall upon it through a narrow slit in the window shade of a darkened room. If we let the rays which pass through the prism fall upon a white screen, we can see a *band of seven colors.* Such a band of colors is called a *solar spectrum.* This experiment shows that sunlight is complex and that it is composed of several colors; it is *polychromatic light.* If light consists of one color only, it is said to be *monochromatic.*

Such a method of *analyzing* complex light, or separating it into its colors is called *dispersion of light.* Such dispersion is due to the fact that some colors are refracted more than others as they pass through a glass prism. Fig. 530 shows the order in which the seven colors appear on a screen. Violet light is refracted more than any other color, since it has the shortest wave length. Red rays are bent least in passing through a prism; they are the longest of the light waves. The other colors lie between the red and the violet. The rainbow, which will be more fully explained later, is a beautiful example of a solar spectrum cast across the sky by the dispersal of sunlight from drops of falling water.

**477. What determines the color of light?** Just as the pitch of a sound depends upon the number of vibrations which reach the ear per second, so the color of light depends upon the number of vibrations which reach the eye per second. *Color bears the same relation to light that pitch does to sound.* When we hold one end of an iron poker in the fire, the electrically charged particles in its atoms oscillate faster and faster as the temperature rises. Soon the vibration rate becomes fast enough to give off waves to which the eye is sensitive. The first color which the eye can detect is a *very dark red.* To produce this dark red color, the vibrations must be so rapid that the wave length produced is only 0.00081 mm. in length.

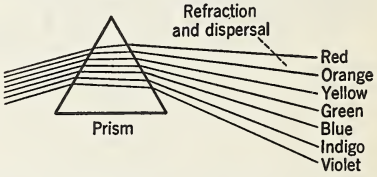


Fig. 530. The prism disperses compound light.

---

## Vocabulary

Analysis, taking apart, or decomposing.
Synthesis, putting together, or combining.
Achromatic, without color.
Polychromatic, composed of many colors.
Polarized, light given a definite direction, or vibrating in one plane only.
Daltonism, color blindness.
Monochromatic, consisting of one color only.
Spectrum, a band of colors formed by dispersing polychromatic light.
Dispersion, the separation of complex light waves into their component colors.

Longer waves than this affect our temperature sense and are known as *infrared rays*, but the eye is not sensitive to them. Let us continue to heat the poker; it gives off *orange* light, then *yellow*, and it finally becomes *white hot*. If we pass the rays from the white hot poker through a prism, we shall have a band of colors like the solar spectrum.

The shortest waves which the eye can see are those produced by violet light; its waves are only 0.00039 mm. in length. Shorter waves, such as those of ultra-violet and X rays, are known, but the human eye is not sensitive to them. Table 18, in Appendix B, shows the entire range of waves to which the eye is sensitive.

A study of the table shows that the eye is affected by a range of frequencies equivalent to only about one octave, since the vibration rate needed to produce violet is just a trifle more than double that required to produce red light. The formula,

$$v = nl,$$

applies to light waves as well as to sound waves. The velocity of light is about 300,000 kilometers per second, or 300,000,000,000 mm. per second. Let us divide this number by the wave length for pure violet, 0.00041 mm. We find that the electron particles in the atom must be vibrating more than $73 \times 10^{13}$, or 730 trillion, times per second to produce violet light.

**478. What determines the color of objects?** It is difficult for pupils to think of color as a property of light waves rather than of objects. For example, we have a piece of cloth which we say is blue, but if we hold it in the red portion of a solar spectrum in a darkened room, we find that it seems black. If we put a piece of red cloth in the blue portion of such a spectrum, it will also appear black. *The color of an opaque object depends upon the kind of light which it is capable of reflecting to the eye. If an object reflects all the sunlight colors which it receives, we say that it is white. We call an object black if it absorbs all the light rays that fall upon it.* What do we mean by saying that an object is blue? *We mean that it absorbs all the light except blue, but it reflects the blue light to the eye.* An object is called red if it absorbs all other colors and reflects red light. Of course, a piece of blue cloth will appear black in the red portion of the spectrum, because there is no blue light there for it to reflect, and it absorbs all other colors. For the same reason, red will appear black in the blue portion of the spectrum.

From these observations, we must conclude that the color of an opaque object depends upon: (*a*) the color of the light that it can reflect; (*b*) the color of the light that shines upon it. Strictly speaking, color is a property of light waves that is dependent entirely upon their length.

*Artificial* lights are likely to be deficient in certain colors, particularly in the blue and the violet. Hence, a turquoise dress that appears to be blue in sunlight may look quite green by artificial light. The mercury vapor lamp, which is widely used by photographers, is deficient in red and yellow rays. A person sitting under the rays of such a lamp loses his natural color. Upon a certain occasion, a child posed by a photographer under such a lamp looked so pale and ghastly that his mother grabbed him and rushed to the doctor. That photographer now uses other artificial lights with his vapor lamp.

The color of *transparent* objects depends upon the color of the light waves which they transmit. Ordinary window glass, which transmits all colors, is said to be colorless. Red glass absorbs all colors but red, which it transmits. The stars of the United States flag would appear red on a black field, if viewed through red glass.

**479. How can colors be combined?** If compound, or polychromatic, light can be analyzed into its simple colors, it seems reasonable to suspect that one can combine simple colors to form compound light. This can be done in two ways.

1. If we place a *second* prism, arranged as in Fig. 531, in the solar spectrum formed by a prism, the different colors will recombine to produce white light. Other colors may be compounded in the same manner.

2. If we have given a disc which has the spectral colors painted upon it, as in Fig. 532, we may combine the colors by rotating the disc rapidly. Since we have duration of vision, the light from one color forms an image which persists on the retina until each of the other colors in turn has been reflected to the eye. We really see them all at one time, and if pure spectral colors are used, they will blend to produce white light. Because certain colors fade rapidly, pure white is seldom seen when this experiment is performed.

**480. What are complementary colors?** In a darkened room let us repeat the experiment with the prisms of Section 476. If we shove an opaque cardboard into the spectrum formed by the first prism at the point $C$ of Fig. 531, we can cut off the *red* rays. The other six colors will combine as they pass through the second prism to form *green* light. By subtracting red light from white light, we produce green light. It appears safe to guess that *red light and green light will combine to produce white light*, and it can be shown by using the rotating disc with the two colors that our guess is correct. *Any two colors that unite to form white light are said to be complementary.*

In a similar manner it can be shown that blue and yellow are complementary colors. White goods acquire a yellow color after continued laundering. Blueing is used in the rinse water to neutralize the yellow color and make the wash white. Iron present in the sand used for making glass imparts to the glass a green color. Manganese imparts to the glass an amethyst or purplish-red color. If the two are used in the right proportion, the glass will be colorless.

**481. Which are the primary colors?** Because sunlight is composed of seven colors which cannot be analyzed further, these seven colors are sometimes

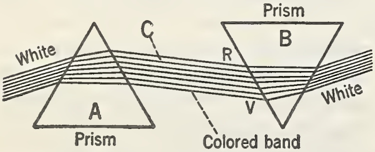


Fig. 531. A second prism may be used to recombine colors in the synthesis of light.

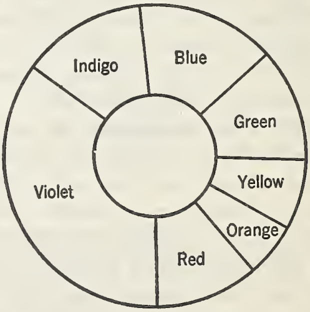
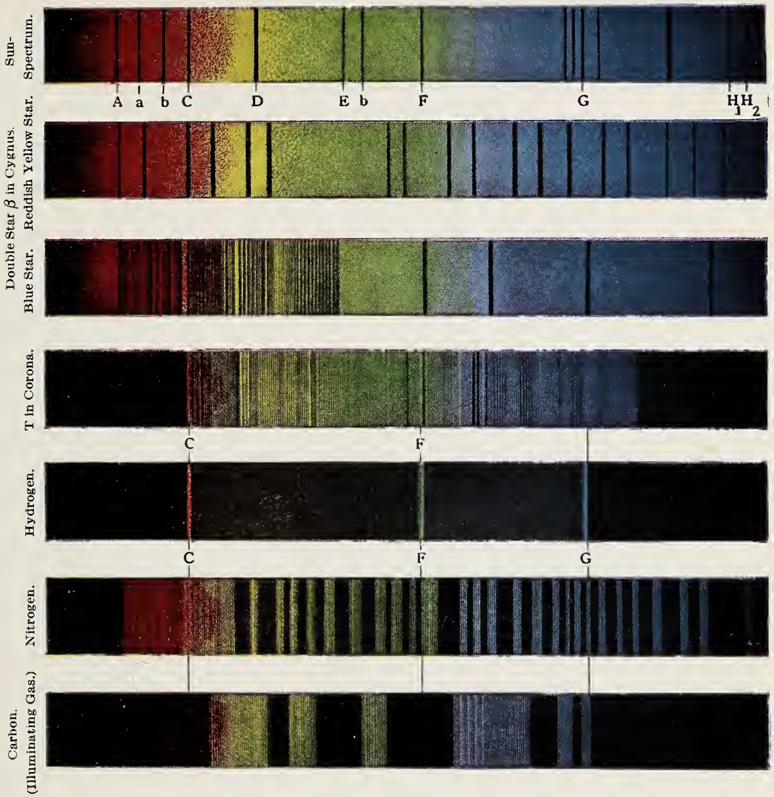


Fig. 532. A disc colored as indicated gives white light when rotated rapidly.


Sun-Spectrum.
A
a
b
C
D
E
b
F
G
$H_1$
$H_2$
Double Star β in Cygnus.
Reddish Yellow Star.
Blue Star.
T in Corona.
C
F
Hydrogen.
C
F
G
Nitrogen.
Carbon.
(Illuminating Gas.)

Spectra of the Fixed Stars and Nebulae Compared with the Sun-Spectrum and Other Spectra

known as *elementary colors*. We have already learned that they combine to produce white light.

Experiment shows that white light may also be produced by combining any two complementary colors. *Three colors* have been found that will produce not only white light, but if they are combined in the right proportions, *any* color can be formed. Hence they are called *fundamental* or *primary colors*. The primary colors are *red*, *green*, and *bluish-violet*.

By the use of Von Nardoff's color apparatus, the effects of mixing the different primary colored lights may be shown. By means of a lantern white light may be thrown upon a screen through three round openings in the color apparatus. In each opening we may place a glass slide. One is colored *red;* a second, *blue*, or *bluish-violet;* and the third, *green*. Note that these are the three *primary colors*. The slides may be so moved in this apparatus that the inner edges overlap, as shown in Fig. 533. Where the three overlap, the three primary colors combine to produce white light. The overlapping of the green and red produces *yellow;* of the red and blue, *purple* or *crimson;* and of the blue and green, *blue-green*, or *peacock-blue*. If we use the blue and yellow together without the other colors, we have white light, since they are complementary. Taking yellow from the white leaves the blue, which is opposite in the figure. In the same manner, taking red light from white leaves the blue-green or peacock-blue; taking green from white light leaves the color shown opposite in the figure, purple or crimson.

**482. What is the theory of color?** It is of interest to inquire how light waves of different length affect the eye in such a manner that we see different colors. The most generally accepted theory of color sensation was proposed by Dr. Thomas Young and later elaborated by Helmholtz. It is based upon the *three primary colors*. According to the Young-Helmholtz color theory, the retina of the eye is provided with three sets of nerves, each set being sensitive to one of the three primary colors.

If all three sets of nerves are equally stimulated, we receive the sensation of white. Of course, blackness or darkness is the result of no stimulation. When red waves enter the eye, they stimulate *chiefly* the nerves that produce the sensation of red, and we see that color. If only those nerves that are sensitive to green are stimulated, the sensation of green is produced in the brain. When yellow light enters the eye, both the red and the green sets of nerves are stimulated. The brain identifies purple if the nerves sensitive to red and bluish-violet are both stimulated. Thus all the colors and shades are produced by the proper stimulation of one, two, or three sets of color nerves.

**483. What is meant by color blindness?** You would not care to ride on a

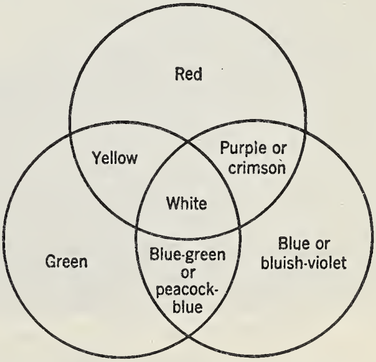


FIG. 533 The overlapping colors combine to produce the colors indicated.

train if the engineer could not tell a red light from a green one. Neither would you feel very safe to ride in an automobile if the driver of the car could not distinguish between green and red. Such persons are *color-blind.* The poet Whittier is said to have patched a green wallpaper in his library with a bright crimson pattern. John Dalton, who was a Quaker and wore somber colors, at one time appeared on the street wearing red stockings; to him they appeared gray.

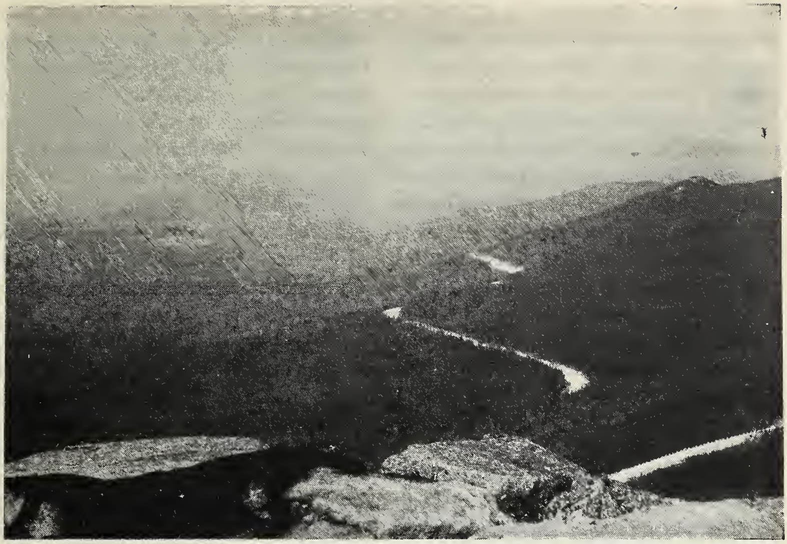
Because Dalton was the first to study this defect in the eye, color blindness is sometimes called Daltonism. It is a defect in the eye itself. In its most common form, one set of color nerves appears to be lacking, and the person cannot tell red from green. In other cases, two or even three sets of color nerves are lacking. In extreme cases, the person's eye is sensitive to lights and shadows only. A person who is color-blind cannot distinguish between red cherries and green, and he is not fitted to pick strawberries. Some 3 or 4% of men are color-blind, and about one woman in 200. The defect is usually congenital, and there is no cure for it. It is claimed that some cases have been caused by the use of alcohol or tobacco.

**484. What is retinal fatigue?** Possibly most pupils have had the following experience: After reading in strong sunlight the outside page of a newspaper printed on pink paper, one finds that the inside page of white paper appears green. We may suspend a bright red disc on a white background in strong sunlight. After each pupil has looked intently at the disc for about one minute, he will see a green spot the size of the disc when he looks at the white background. This phenomenon is due to *retinal fatigue.* The retina of the eye tires of red and refuses to be stimulated by it any longer; the other six colors reflected by the white background combine to produce the green color. Red and green are complementary colors. When we repeat the experiment, using a blue disc, the spot that appears after the eye tires of blue, is yellow.

**485. What is the result of mixing pigments?** When we *add* blue and yellow *light*, we have white light produced. If we mix a blue *pigment* with a yellow one, we do not have white produced, but green. Each pigment *subtracts* certain colors. For example, the yellow *subtracts* or absorbs blue and violet, and the blue *subtracts* or absorbs red and yellow. Green is the only color that is not subtracted by either pigment; hence these two pigments produce green.

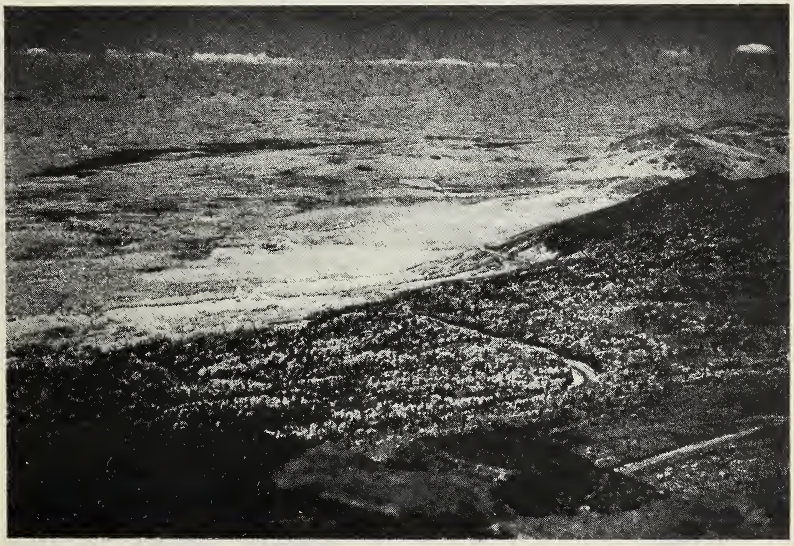
When we mix pigments, each one always subtracts certain colors from white light; the resulting color depends upon the light waves that are not absorbed. The *primary pigments* are the complements of the three primary colors. They are, respectively, *peacock blue* (red), *crimson* (green), and *yellow* (bluish-violet). When the three primary pigments are mixed, all the colors are subtracted from white light, and the mixture is black.

**486. What is three-color printing?** In three-color printing, three negatives of the same object are made through three color screens, each stained with one of the three primary colors. Half-tone blocks are then made from these negatives in the usual manner. The colored plate is then printed on white paper, first with yellow ink, then with red, and finally with blue. The accuracy of the color reproduction depends upon



*Courtesy of the Eastman Kodak Company*

FIG. 534. A photograph from Whiteface Mountain taken with an ordinary film with no filter. Note the loss of detail and the indistinctness of the distant view.



*Courtesy of the Eastman Kodak Company*

FIG. 535. The same photograph as that of Fig. 534, taken by use of an infra-red sensitive plate. Observe the improvement in detail.

the selection of inks of a shade exactly complementary to the shades used in making the screens. (See frontispiece.)

**487. How has photography been improved?** Improvements in mechanism have enabled persons to take pictures with shorter exposures. Fast lenses have been developed. The picture shown in Fig. 534 was taken by the usual method with light which is visible to the eye. The same picture is shown in Fig. 535, but in this case a filter was used so that the picture could be taken with infra-red rays. It is easy to see why infra-red photography is so useful, especially in wartime, since clouds and haze do not interfere with clearness.

Colored films, too, are popular at present. By reference to the plate for making colored film, we shall be able to understand how colored motion pictures can be taken by the *kodachrome process*, which is one of several processes that are now in use.

The celluloid film is coated with three sensitive layers, separated from each other by extremely thin layers of plain gelatin. The bottom layer is an emulsion which is sensitive to red. The middle layer is a green-sensitive emulsion, and the top layer is sensitive to blue. The three layers, with the two sheets of gelatin separating them, are not more than 0.02 mm. in thickness.

Blue light is absorbed by the top blue-sensitive emulsion upon which it makes its impression. Green light passes through the top layer and is absorbed by the middle green-sensitive layer, upon which it acts chemically. Red light, after passing through the two sensitive layers, acts upon the bottom layer of red-sensitive emulsion. The back surface of the film is coated black to prevent reflection of light.

Such a colored film does not give good effects unless the exposure is made in direct sunlight. The camera, too, must have a very fast lens in order to give good results. After being exposed, the film is sent to the manufacturer to be developed. The technique used in developing the film, reversing the images, and then dyeing the different layers is too intricate to be discussed here.

**488. There are different kinds of spectra.** We know that the sun's rays are separated into colors by a prism to form a solar spectrum. Light from other sources may be analyzed in the same manner. There are three kinds of spectra:

1. *Continuous.* A platinum wire held in the colorless flame of a burner produces a spectrum that consists of an *unbroken band of seven colors.* Since the seven colors form one unbroken band,

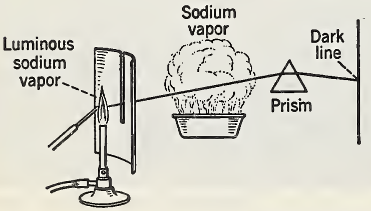


Fig. 536. Non-luminous sodium vapor absorbs the yellow light produced by luminous sodium vapor.

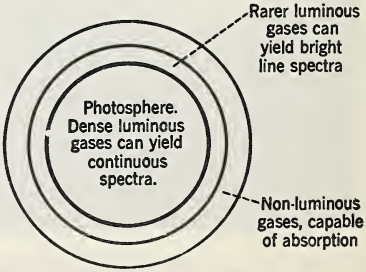


Fig. 537. The sun's atmosphere causes it to give absorptive spectra.

such a spectrum is said to be *continuous. Continuous spectra are produced by incandescent solids, liquids, and dense gases.*

2. *Discontinuous.* Let us dip a platinum wire into a solution of common salt, or sodium chloride, and then hold the wire in the colorless flame of a burner surrounded by a piece of metal in which a narrow slit has been cut. When the light coming through this slit falls upon a prism, the spectrum which it forms on a screen consists of a single line of a bright yellow color. *Luminous gases or vapors under atmospheric pressure give bright-line spectra.* Such a bright yellow line in a spectrum is characteristic of all compounds that contain sodium. When the spectrum produced by the hot platinum wire and the luminous sodium vapor are examined together, we find that the platinum produces the band of colors, but that the sodium vapor gives a bright line in the yellow of the spectrum. It always appears in a certain part of the spectrum. Since this bright line breaks the continuity of the band of colors, such *bright-line* spectra are known as *discontinuous spectra.* Luminous vapors containing compounds of calcium produce two bright lines, one in the green and the other in the red. The colored spectral chart (facing p. 398) shows the three bright lines produced by hydrogen.

3. *Absorptive.* We may produce bright-line spectra with luminous sodium vapor just as before, and then place an iron pan containing sodium chloride between the slit and the prism, as in Fig. 536. When the pan is heated enough to vaporize the sodium chloride, but not hot enough to make it luminous, a dark line appears in the spectrum where the yellow line had previously appeared. The yellow light waves have been *absorbed* by the sodium vapor. Such spectra are called *dark-line*, or *absorptive spectra. Gases or vapors can absorb light waves of the same length they would produce themselves, if they were heated to luminosity.* For example, *luminous* sodium vapor gives bright yellow light waves. *Nonluminous* sodium vapor absorbs yellow light waves.

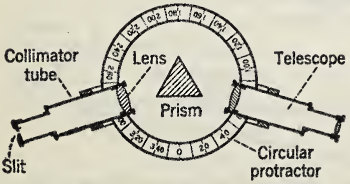


FIG. 538. The spectroscope is used to study spectra.

**489. What are Fraunhofer lines?** As early as 1802, Wollaston noticed that certain dark lines appear in the sun's spectrum when produced by a prism and a narrow slit to admit the sun's rays. Ten years later they were independently discovered by Fraunhofer, who charted a large number of these dark lines. He observed that they always appear in the same position in the spectrum, and that the position is the same as that occupied by the bright lines caused by the luminous vapors of different elements. Since about 600 of these lines were charted by Fraunhofer, they are known as *Fraunhofer lines.*

From a consideration of Fig. 537, we can understand why the sun produces absorptive spectra. The photosphere consists of highly compressed gases, which would form continuous spectra if the sun had no atmosphere. The chromosphere consists of luminous gases under less pressure. They would produce bright-line spectra, if they could be examined alone. In the outer portions of the sun's atmosphere, there are undoubtedly non-luminous vapors which absorb the waves that might produce bright-line spectra. Hence the sun yields absorptive spectra. Better methods of producing a long spectrum have been produced than those used by Fraunhofer. In such a spectrum the number of lines is almost unlimited.

**490. What is a spectroscope?** The spectroscope is an optical instrument used for examining spectra. It consists of a prism, Fig. 538, mounted on a circular protractor. The collimator tube receives light through a narrow slit, and transmits it through the lens so that the rays are parallel as they strike the prism. A small telescope magnifies the spectrum which is produced by the prism. Cross-threads in the telescope may be focused on any line in the spectrum. Both the collimator tube and the telescope are mounted on a circular protractor, so that the angular position of any line may be carefully measured.

**491. What is meant by spectrum analysis?** Although Fraunhofer charted some of the dark lines in the solar spectrum as early as 1812, it was not until 1859 that the spectroscope began to be used for the analysis of compounds in testing for elements. At that time, Bunsen and Kirchhoff, two German chemists, introduced the use of the spectroscope for analytical work. We have seen that sodium compounds always give a bright yellow line when examined by a spectroscope. This test is so delicate that less than one millionth of a milligram of sodium can be detected by means of the spectroscope. Several elements have been discovered in this way. In 1860 Bunsen discovered *cæsium* and *rubidium* by the use of the spectroscope. The former is so named because it gives two blue lines in the spectrum, and the latter because it yields two red lines. Discoveries of several new elements by the aid of spectroscopic analysis have been reported during the last decade.

As early as 1868, helium was discovered in the sun's atmosphere by Sir Norman Lockyer. It was not found in the earth's atmosphere until 1895. By means of the spectroscope, astronomers are able to determine the composition of the sun and other celestial bodies which are hot enough to be luminous.

**492. What causes the rainbow?** When the sun shines upon drops of falling water, a solar spectrum may be formed. Water disperses light in the same manner as a prism, but reflection and refraction of light are also important in forming the rainbow. Fig. 539 shows the path that a beam of sunlight takes in passing through a drop of water. As it enters the drop at *A* it is refracted; dispersal also occurs. The red ray suffers total reflection at *R* and the violet at *V*. When they leave the drop at *B* both rays are again refracted. The angle which these refracted rays makes with the horizon of an observer as he stands with his back to the sun is 40° for the violet, and 42° for the red rays. In the actual bow which the observer sees, the red rays come from

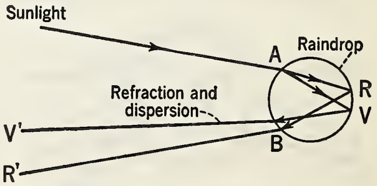


FIG. 539. A rainbow is produced by refraction, total reflection, and dispersion of light.

drops of water at an angle of 42°, and the violet from those at an angle of 40°. The other colors are formed by drops between these angles. The rainbow is an arc, since the eye of the observer is at the tip of a cone from which he sees the colored rays refracted from drops in all directions at angles of from 40° to 42°.

Sometimes a larger *secondary* bow is seen above the *primary*. The colors are here reversed, the violet being on the outside. The light is refracted from drops of water at an angle of from 51° to 54°. It enters the lower part of the drop, is refracted and dispersed as in the primary bow, but it is *twice totally reflected* before it leaves the drop. For this reason more light is absorbed, and the secondary bow is always fainter than the primary bow.

**493. What is chromatic aberration?** Light passing through the edge of a lens undergoes spherical aberration. In our experiment with the prism we learned that different colors have different indexes of refraction; therefore light is also dispersed in passing through a lens. Since the violet light is bent more than the other colors, it is brought to a focus more quickly. (See Fig. 540.) A screen placed at *S* shows an inner ring of violet surrounded by the other colors. If the screen is moved to the position *S*′, the inner ring will be red. Images formed by ordinary spherical lenses are always fringed with spectral colors. *The non-focusing of light of different colors is called chromatic aberration.*

**494. What is the remedy for chromatic aberration?** The fringe of colors around the image formed by an ordinary lens is a nuisance. It interfered in the use of optical instruments until the latter part of the eighteenth century. Then Dolland discovered that chromatic aberration can be remedied by using a combination of lenses. By using a double convex lens made of crown glass with a plano-concave lens made of flint glass, the dispersal of the light may be corrected without preventing refraction and image formation. A lens combination of this type is called an *achromatic* (without color) *lens*. High-grade optical instruments are fitted with lens combinations which are corrected for both spherical and chromatic aberration.

**★495. Is interference of light possible?** Just as one sound wave may be so superimposed upon another as to strengthen or to diminish the sound, so one light wave can be superimposed upon another to produce *interference*. If we clamp together two round plates of glass, one of them plane and the other *very slightly* convex, we shall have between them a wedge-shaped film of air which is about as thick as the length of a light wave. If a sodium flame, which gives yellow light only, falls upon such a device, one can see alternate yellow and dark bands. Reflection occurs from both surfaces of the glass, and of course the wedge-shaped film of varying thickness will cause some reflected waves to meet in the same phase and others in the opposite phase. Where they meet in the same phase we see the *yellow bands*. Where they meet in opposite phase,

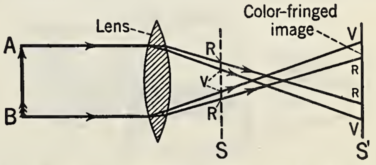


Fig. 540. Chromatic aberration is a defect in lenses.

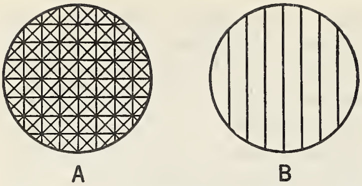


Fig. 541. *A*. Possible appearance of the end of a beam of light. *B*. Appearance of polarized light.

they interfere and produce *dark bands*. When sunlight falls upon the device, we see a band of spectral colors, since the wedge-shaped air film causes different colors of *different wave lengths* to interfere at different positions. In the same manner, the air film between oil and water, or in a cracked piece of ice, will show spectral colors when viewed at an oblique angle in such a way that the film will be of varying thickness. It is difficult to explain interference of light by any theory except the wave theory.

**★496. What is diffraction?** When the wave theory was proposed, its opponents argued that light waves should bend around corners and not cast shadows. It is possible to show by experiment that very short sound waves do cast shadows, and also that light waves under some conditions are bent out of their straight course. When light waves pass through an opening which is small in comparison with the lengths of light waves, they spread out and produce spectral colors as they interfere with one another. This phenomenon, which is called *diffraction of light*, may also be produced by reflection of light from a surface which is covered with exceedingly fine striations.

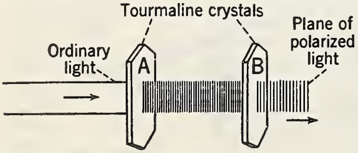


Fig. 542 How tourmaline crystals are used to polarize light.

By means of a diamond point, 15,000 to 30,000 lines to the inch have been ruled on glass, or on speculum metal. Such a ruled plate is called a *diffraction grating*. With a glass grating, light is transmitted through the narrow space between the lines and spreads out, or is diffracted. Such a grating is much better than a prism for examining spectra, since the colors do not overlap and the spectrum that is produced may be several feet in length. The plumage of some birds, and some changeable silks have a beautiful play of colors on account of diffraction. One company is making cellophane with a striated surface. It gives a beautiful play of colors when so used for decorative effects that light can shine through it.

**★497. What is polarized light?** If we could look at the end of a beam of light, we should probably see some of its transverse waves vibrating from side to side, some up and down, and others at various other angles as represented in Fig. 541. Certain crystals, tourmaline for example, transmit only those waves which are vibrating in the same plane as the axis of the crystal. When light passes through such a crystal, we have *polarized light*.

Suppose that we have two tourmaline crystals with their axes parallel, as in Fig. 542. A complex beam of light enters the first crystal at *A* and is

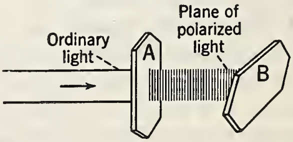


Fig. 543. Light is stopped entirely.

polarized; it passes through both crystals as a plane of polarized light because both their axes lie in the same plane. Suppose we turn one of the crystals of tourmaline so that its axis is perpendicular to that of the other, as in Fig. 543. The light is polarized by the first crystal, but it is stopped by the second crystal and no light is transmitted through both of them. We can make a rope vibrate in an up-and-down direction through a picket fence, but not from side to side. Through horizontal slots we can make it vibrate from side to side, but not up and down. (See Fig. 544.) Through a lattice structure, its vibrations in all directions are stopped. The tourmaline tongs of Fig. 545 may be used to demonstrate polarization. We can see through both crystals when their axes lie in the same plane, but we cannot see through them when their axes are perpendicular to one another.

★**498. What is the polariscope?** This instrument has a *polarizing* crystal at one end of a tube two feet or more in length. Monochromatic light enters this *polarizer* and is polarized by it. At the end of the tube near which the eye is placed there is a similar crystal called an *analyzer*. It is mounted in a rotating head so that it may be turned through any number of degrees. Some chemicals have the ability to twist or turn a plane of polarized light. Glucose, sugar, tartaric acid, and some other organic compounds have this property.

Suppose that we turn the analyzer so that it transmits no light at all. Then we may place a sugar solution in the tube between the polarizer and the analyzer. It will twist the plane of polarized light and permit it to pass through the analyzer. By finding out how many degrees the analyzer must be rotated to make the field dark again, it is possible to determine the percentage of sugar in the solution. The amount of such rotation varies with the kind of substance and with the strength of the solution. The polariscope is much used in sugar refineries. If it is graduated to read per cent of sugar directly, it is called a *saccharimeter*. Substances which twist the plane of polarized light to the right are called *dextro-rotatory*. Dextrose is an example. A substance which twists the plane of polarized light to the left is said to be *levo-rotatory*. Levulose is a kind of sugar which takes its name because it has this property.

**499. What are some other uses for polarized light?** For several years manufacturers of motor cars have been using polarized light to examine material to learn how it behaves under an applied stress. The strains in the material show clearly under polarized

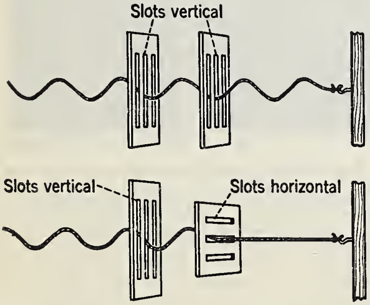


FIG. 544. Rope vibrations are analogous to polarized light.

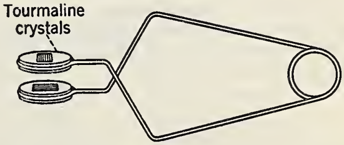
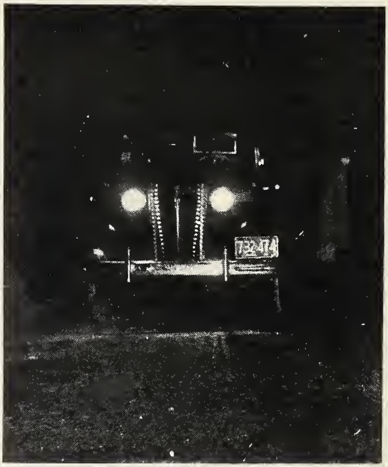


FIG. 545. Tongs which have tourmaline crystals.

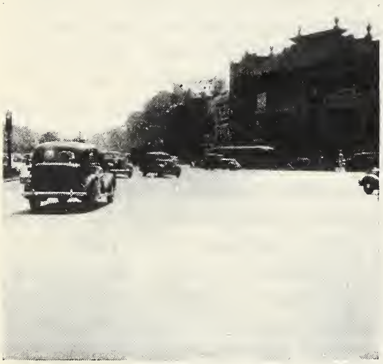
*Courtesy of the Polaroid Corporation*

Fig. 546A. This picture shows how an on-coming car appears to one who is driving at night. A driver meeting such a car is temporarily blinded by the glare. It is difficult for him to see the edge of the highway.



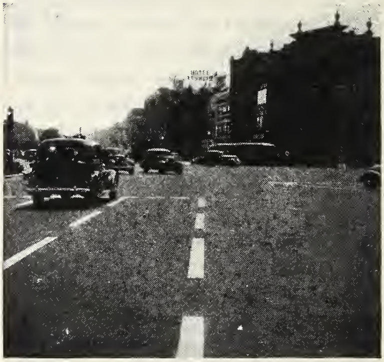
*Courtesy of the Polaroid Corporation*

Fig. 546B. In this view the on-coming car is equipped with Polaroid headlight lenses. The other driver views the car and road through a Polaroid visor. Note the figure appearing from the rear of the car.



*Courtesy of the Polaroid Corporation*

Fig. 546C. A simultaneous picture of 546D taken through a non-polarizing absorption filter. Observe that the glare is not eliminated.



*Courtesy of the Polaroid Corporation*

Fig. 546D. A glaring highway surface as seen through Polaroid material so set that it blocks horizontal light vibrations reflected from the highway. Little or no glare.

light. Building materials, too, can be tested in the same way. The chemist not only uses polarized light to analyze sugar and certain chemicals, but he uses it to learn the identity of some tiny crystals.

Many accidents on the highway have occurred because a driver was blinded by the headlights of an approaching car. A kind of sandwich glass contains tiny crystals which are capable of polarizing light. If the headlight lens is made of such a glass, which is known as *Polaroid,* such a lens will act just like the *polarizer* of a polariscope and permit only plane polarized light to pass. If the windshield of an approaching car is also fitted with such Polaroid glass, set at right angles to the plane of polarized light, it will act as the *analyzer* and cut off the glare from the approaching headlights. (See Fig. 547, which shows the dark field caused by the overlapping or two pieces of Polaroid glass.) It is possible, too, to buy Polaroid glasses. The driver who wears such glasses can see the light given by his own headlights, but he is not blinded by the headlights of an approaching car, provided the lenses of such a car are equipped with Polaroid glass.

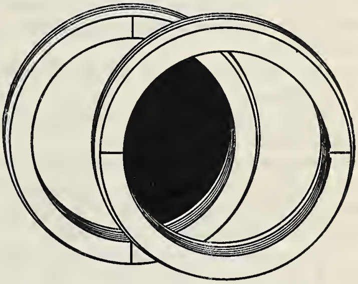


FIG. 547. Polaroid glasses are used to reduce glare.

## Summary

Since light waves of different color have different refrangibility, light is scattered or dispersed by refracting media. Dispersal from raindrops produces the rainbow. The dispersion of light by lenses which produce a color-fringed image may be remedied by the use of achromatic lenses.

Color is analogous to pitch; it depends upon the length of the light waves, or upon the frequency of vibration. The color of an opaque object depends upon the color of the light it receives and upon the color of the light it can reflect. Any two colors that combine to produce white light are complementary.

Incandescent solids, liquids, and compressed gases yield continuous spectra; luminous gases produce bright-line spectra. Gases absorb light waves of the same length they would emit if heated to luminosity.

*How many of the following terms can you define or explain? (You probably will not remember them all from one reading.)*

Dispersion of light
Color of transparent objects
Complementary colors
Theory of color
Retinal fatigue
Fraunhofer lines
The rainbow
Interference of light
Polarization of light
Color of opaque objects
Primary colors
Color blindness
Three-color printing
Kinds of spectra
Spectroscope
Chromatic aberration
Diffraction
Polaroid glass

## QUESTIONS

1. What do we mean when we say that an object is red?

2. The mercury vapor lamp is deficient in red rays. What effect does its light have upon the appearance of persons in a room where it is used?

3. Doppler's principle applies to light waves. A luminous body moving toward the earth has its light waves shortened. Would the lines of its spectrum be displaced toward the violet end of the spectrum or toward the red?

4. Do two persons see the same rainbow? Explain.

5. Why is the rainbow curved? Can the complete circle ever be seen?

6. Do you think it possible to have a rainbow at noon in July? Is a rainbow at noon possible in January? How would the latitude of a place affect your answer?

7. Does iron which is heated white hot give off red rays of light? How could you prove your answer?

8. If black objects absorb all the light they receive, how is it that we see them?

9. What color do objects appear when viewed through a piece of red glass?

10. How would your school colors appear if viewed through a piece of blue glass? If viewed through a piece of red glass? How does the United States flag appear when viewed through blue glass? If it is viewed through red glass?

11. If a lady has a sallow or yellowish complexion, what color can she add to her face powder to neutralize the yellow tint?

12. Why is it undesirable to use blue paper, a blue rug, or blue draperies in a room that has a northern exposure? What colors may be used?

13. For selecting colors, the so-called daylight bulb is used. The bulb is tinted blue. Explain.

14. What color does a blue serge suit appear when examined by artificial light? Explain.

15. A ribbon which appears blue by daylight may seem green when viewed by artificial light. Explain.

16. In what ways has the introduction of spectrum analysis been very important?

17. Why should an applicant for a license to drive an automobile be required to pass a test for color blindness?

18. Why does milk lose its rich color when put in glass jars or bottles which have a green color?

19. Which colors are restful to the eye, and which colors are irritating if viewed for some time?

20. Are complementary colors harmonizing colors?

# Unit Nine

# *Magnetism and Static Electricity*

## Preview

ONE OF THE MYSTERIOUS FORCES WHICH WE HAVE studied is the force of gravitation. We can see *how* gravity acts. It is doubtful if anyone has the faintest idea *why* the earth attracts objects to itself, or why one heavenly body attracts another which may be billions of miles distant.

As we begin the study of the attractive force known as magnetism, we find it equally mysterious. We shall learn many facts concerning magnetism, such as the method of making or destroying a magnet, the materials which are attracted by a magnet, something concerning the polarity of magnets, how magnetism may be induced in a piece of iron or steel by a magnet, and how man uses this mysterious force in several important ways. It may seem even stranger to learn that a magnet may repel a body than it is to find out that a magnet may attract certain substances. Then, too, we find it no less puzzling when we learn that the earth itself acts as a huge magnet with magnetic poles a few hundred miles distant from its geographic poles. The compass needle serves as a guide to indicate directions because it aligns itself along the magnetic meridians which pass from one magnetic pole of the earth to the other.

One of the fascinating things about magnetism is its close relationship with static electricity. In many ways the two are alike. There are two poles of unlike sign for every magnet. Electricity is of two kinds, positive and negative. Like poles repel each other, and so do like charges of electricity. Unlike poles attract each other, and so do unlike charges of electricity.

An electric charge in motion produces an electric current. If such an electric current flows through a conductor, it sets up a magnetic field around the conductor. This fact makes it possible to make an electro-magnet, which has so many uses that one wonders how we could get along without it. In the dynamo, or electric generator, we make use of the fact that a magnet can produce an electric current. We are indebted to Benjamin Franklin for our first knowledge of atmospheric electricity. His experiment of flying a kite during a thunderstorm is well-known, but it is not safe for you to repeat it.

# *Magnetism*

## 1. Nature of Magnetism

**500. Where are natural magnets found?** In Magnesia, Asia Minor, beds of iron ore are found which have the property of attracting bits of iron or steel. This ore was discovered by the Greeks, and is called *magnetite*. This black iron ore is found also in the Adirondacks and in certain other localities. Pieces of this ore are known as *natural magnets*.

If an elongated piece of magnetite is suspended by means of a thread so that it will be free to swing or turn in any direction, we find that the magnetite will turn around until it assumes a line that is nearly north-and-south. For this reason natural magnets were called *lodestones* (leading stones). As early as the twelfth century, lodestones began to be used to indicate directions, much as the magnetic compass is now used.

**501. How can we make a magnet?** Probably before the Christian era, the ancients had learned how to magnetize iron by rubbing it on a piece of lodestone. Lodestone is now little used, because *artificial magnets* which are much better than the natural magnets can be made easily. If we wish to make a magnet, we may use a bar of steel. Half of a steel knitting needle works satisfactorily. Holding the bar of steel in one hand, we stroke it with *one end of a magnet*, always beginning from the same end. To do so, the magnet must be brought back through the air to the end from which we started, as shown in Fig. 548. Other methods of making a magnet are discussed later.

**502. What materials are magnetic?** Everyone knows that a magnet will attract bits of iron and steel. Such sub-

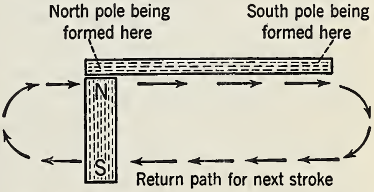

North pole being formed here
South pole being formed here
N
S
Return path for next stroke

Fig. 548. The bar may be stroked as indicated in order to form a magnet.

---

### Vocabulary

Declination, angular deviation of the compass needle from the true North.

Permeable, readily conducting magnetic lines of force.

Residual (*residue*), a part remaining.

Induction (*inductio*, act of leading in), the act or process by which a body becomes magnetized or electrified by the presence of a magnetized or electrified object.

Isogonic (*iso*, the same; *gonia*, angle), pertaining to a line drawn through places having the same declination.

Isoclinic (*iso*, the same; *klinein*, to incline), pertaining to a line drawn through places having the same dip.

Diamagnetic, repelled by a magnet.

Permalloy, a permeable alloy consisting of nickel and iron.

stances are called *magnetic materials.* Two other metals, nickel and cobalt, are attracted by a magnet, although to a lesser degree. Some alloys have been made which are attracted by the magnet, too, but we generally think of iron and steel as the most important magnetic materials.

**503. What materials are non-magnetic?** Most common substances, such as wood, copper, glass, aluminum, brass, etc., are not affected in any way by the magnet. They are said to be *non-magnetic.* A few substances are actually *repelled* by a magnet. They are said to be *diamagnetic.* Bismuth shows this property of diamagnetism to the largest degree, but it is also shown by zinc and antimony.

**504. What is meant by polarity?** Let us sift some *iron filings* on a sheet of paper, and lay a bar magnet in the filings. When the magnet is lifted we find that the filings cling to the magnet *at or near the ends only.* (See Fig. 549.) The magnetic force appears to be concentrated at or near the ends of the magnet, at what is called the *poles of the magnet.* If a magnet about six inches long is used, we shall probably find that there are more iron filings clustered at a distance of about one centimeter from each end than at any other place.

Let us suspend a bar magnet so that it can turn freely, as in Fig. 550, and permit it to come to rest. We shall then find that the magnet points in a nearly north-and-south direction. That pole of a suspended magnet which points toward the north is called a *north-seeking pole;* it is sometimes called merely a north pole, the N-pole, or the + pole. The other pole is the *south-seeking pole,* which is sometimes called a south pole, the S-pole, or the − pole.

**505. What is the law of magnets?** Given a magnet suspended as in Fig. 550. If we bring the north-seeking pole of a second bar magnet near the north-seeking pole of the suspended magnet, we find that the *two poles repel each other.* If we bring the south-seeking pole near the south-seeking pole of the suspended magnet, we find that they repel each other. Hence we conclude that *like magnetic poles repel.*

Let us continue the experiment and bring the south-seeking pole of the magnet near the north-seeking pole of the suspended magnet. We find that they attract. We also get attraction when we bring the north-seeking pole of the magnet near the south-seeking pole of the suspended magnet. We conclude that *unlike poles attract.* We may state the LAW OF MAGNETS as follows:

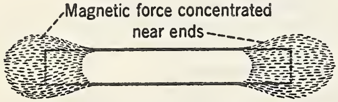


FIG. 549. The filings are clustered around the poles.

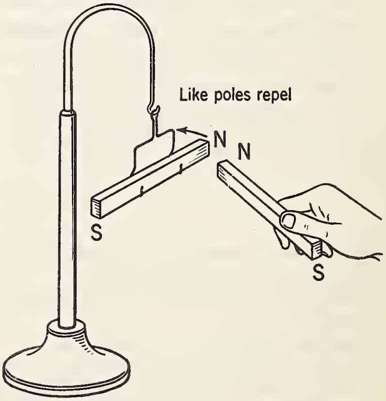
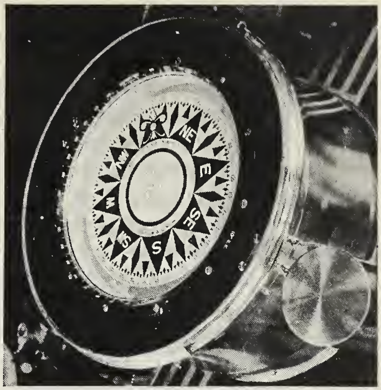


FIG. 550. Like poles repel. Unlike poles attract.

*Like poles repel; unlike poles attract.* The force of attraction is directly proportional to the strengths of the poles and inversely proportional to the square of the distance between them. (See law of gravitation.) A magnetic pole is said to be of unit strength when it repels an exactly similar pole one centimeter distant with a force of one dyne.

**506. What use has the magnetic compass?** Since a magnetized needle that is free to rotate finally comes to rest in a nearly north-and-south line, it is possible to mount such a needle on a pivot and use it as a compass to show directions. (See Fig. 551.) After the invention of the mariner's compass, sailors felt much safer sailing into uncharted seas. The student will recall from his study of history that the explorations which led to the discovery of America followed rather shortly after the compass began to be used to indicate directions. Of course, the compass needle is not an infallible guide. It is affected by metal parts of ships. Later, too, we shall see that the north-seeking pole does not point even approximately north in some regions. The gyro-compass and the radio compass are now largely used.

**507. There are temporary and permanent magnets.** 1. *Temporary.* A piece of *soft* iron is *easily* magnetized but soon loses nearly all its magnetism. Hence, a magnet made of soft iron is only a *temporary magnet.* It is possible to make a magnet by winding a number of turns of insulated wire around an iron core and passing an electric current through the wire. It becomes a magnet quickly when the current passes, and loses it quickly when the circuit is broken. For the core of such an *electro-magnet*, soft iron or silicon steel is used. Silicon steel is an alloy that has little *retentivity;* it loses its magnetism almost instantly. Nearly all temporary magnets retain a little *residual magnetism.*



*Courtesy of Cunard White Star, Ltd.*

Fig. 551. The compass utilizes a magnetic needle.

An alloy made of nickel and iron is called *permalloy.* It is so easily magnetized that if a rod of permalloy is held in a north-and-south line, it becomes slightly magnetized by the earth and will pick up small pieces of permalloy. If it is then rotated through 90° until it is in an east-and-west line, the bits of permalloy will fall off again. No known substance is so easily magnetized as permalloy; no substance loses its magnetism so easily and so completely.

2. *Permanent.* It is difficult to magnetize a piece of hard steel, but when steel is magnetized it retains its magnetism well. Hence, steel is used for making *permanent magnets.* We say that its retentivity is high. Steel containing the metal tungsten alloyed with iron makes excellent permanent magnets. Cobalt is also alloyed with steel to make permanent magnets.

**508. How can steel be demagnetized?** If we break the piece of knitting needle which we magnetized, we do not destroy the magnetism. We shall have two more poles formed. Even if we break it into several pieces, there will always be two poles for each piece, a north-seeking pole and a south-seeking pole. Fig. 552 shows the effect of breaking a magnet into two or more pieces. Next, let us hold a piece of the magnetized needle in the flame of a burner until it is red hot. When we let it cool and then try to pick up some iron filings, we find that it has lost nearly all its magnetism. We conclude that *heating a magnet destroys its magnetism.*

A magnet will lose nearly all its magnetism if we hold it in an east-and-west line and tap it repeatedly with a hammer. Care should be taken to avoid dropping, jarring, or pounding magnets. Another method of demagnetizing objects involves the use of alternating currents of electricity.

**509. What is meant by magnetizing by induction?** If we hold a bar magnet *near* or *in contact with* a soft iron nail, as shown in Fig. 553, the nail becomes a magnet by *induction.* This word comes from the Latin *inductio,* which means "the act of leading in." Magnetism is led into the nail from the magnet. The nail retains its magnetism as long as the magnet is held near it or in contact with it, and it will pick up several tacks, but it loses its magnetism as soon as the magnet is removed. *Magnetism produced in this manner by the presence of a magnet is called induced magnetism.*

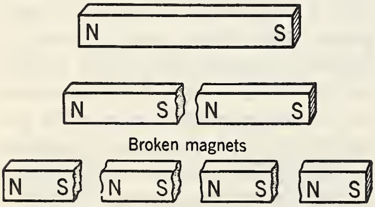


FIG. 552. How is a magnet affected by being broken?

By the use of a small compass needle it can be shown that the nail has polarity while the magnet is held near it, and also that each tack held by the nail is also a magnet by induction. That end of the nail near the north-seeking pole of the magnet becomes a south-seeking pole, and the more remote end becomes a north-seeking pole. When iron filings cling to a magnet, each filing becomes a temporary magnet by induction. In fact, any piece of iron brought near a magnet becomes a temporary magnet.

**510. What are lines of force?** If we place a smooth piece of cardboard over a bar magnet, sprinkle iron filings evenly over the cardboard, and then tap the board gently, the filings will arrange themselves along curved lines, as shown in Fig. 556. Such curved lines are called *lines of force.* If it were possible to get an independent north-seeking pole (without the south-seeking pole) and place it at the north-seeking pole of a strong bar magnet, it would move in a curved path from the north-seeking pole to the south-seeking pole, as shown in Fig. 554. This would happen because it would be repelled by the north-seeking pole of the magnet and attracted by its south-seeking pole, in each case with a force inversely proportional to the squares of the distances between them. *The path that an*

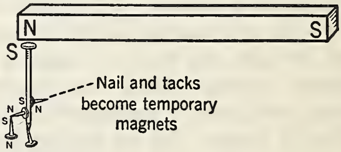


FIG. 553. The nail becomes a magnet by induction. How about the tacks?

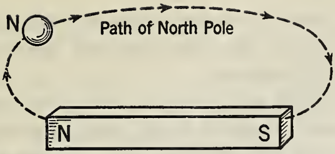


Fig. 554. The line of force as indicated by the path of an independent N-pole.

*independent north-seeking pole would take in moving from the N-pole to the S-pole of a magnet is known as a line of force.*

Of course, it is impossible to get an independent north-seeking pole. If we use a Mayer's floating magnet, which consists of a magnetized sewing needle thrust through a bit of cork large enough to float the needle, we can get a fair approach to the theoretical condition. A bar magnet is placed beneath the trough of water in which the needle floats. (See Fig. 555.) The S-pole of the needle is so much farther from the magnet than the N-pole that the path taken by the floating magnet is essentially a curve similar to that of Fig. 554.

**511. What is a magnetic field?** If we wish to use a compass needle, we must remove all pieces of iron to a distance of a meter or more. The lines of force of a magnet extend out to some distance from the magnet. Any space permeated by lines of force is a *magnetic field.* Such a magnetic field is influenced by any magnetic material brought within the field, and it produces an inductive effect upon the magnetic material. A field of unit strength has one line of force, called a *maxwell,* per square centimeter. The area is always considered as perpendicular to the line of force. A magnetic field of unit intensity is called a *gauss.*

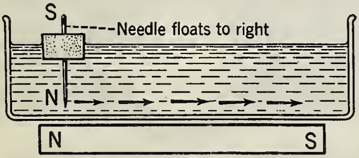


Fig. 555. Path of a floating magnetic pole.

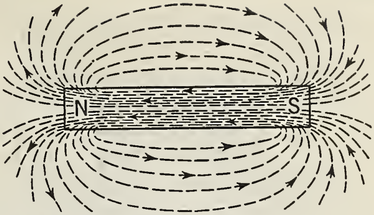


Fig. 556. Chart showing lines of force about a magnet.

**512. How can we map a magnetic field?** One can make a permanent chart of a magnetic field by pinning a blueprint paper over a magnet which rests in a grooved board so that the paper will lie flat. The work should be done in subdued light. If iron filings are sifted lightly and evenly over the surface of the paper, they will arrange themselves in the direction of the lines of force when the board is tapped gently. After the paper has been exposed to the light for a few minutes, the filings are poured off and the print is developed in the usual manner by submerging it in water. Fig. 556 shows the magnetic field with its lines of force about a single bar magnet. If two magnets are used with their like poles adjacent, the flexibility of the lines of force is clearly indicated. (See Fig. 557.)

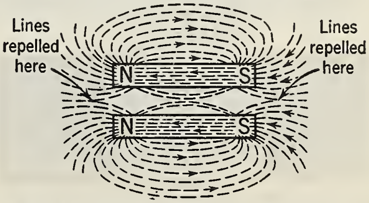


Fig. 557. Lines of force. Like poles repel.

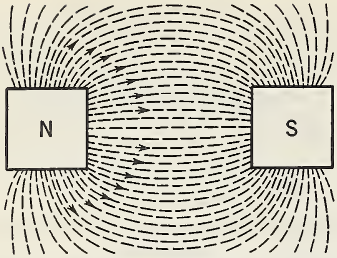


Fig. 558. When unlike poles are adjacent, we get attraction.

We observe that the lines of force repel each other. They really act like elastic bands stretched from pole to pole of the magnet. When two magnets are used with unlike poles adjacent, then the lines of force appear to pass from the north-seeking pole of one magnet to the south-seeking pole of the other. (See Fig. 558.)

**513. What are the properties of lines of force?** From our study of lines of force we may make a summary of their properties:

1. According to the conception of physicists, the lines of force are *closed curves*, extending from the north-seeking to the south-seeking pole through the air, and returning through the magnet.

2. They do not cross one another, but they repel one another. Hence they are farther apart opposite the center of the magnet.

3. We find the lines of force concentrated at the poles; thus they show that the magnetic field is much stronger at or near the poles. They actually picture the direction in which the magnetic force acts.

While such lines of force may seem to the beginner to be quite visionary, yet he will find that they play an important part not only in magnetism, but also in practical electricity.

**514. What are magnetic transparency and permeability?** In Section 512 we learned that magnetic force exerts its influence upon iron filings *through* blueprint paper. Let us repeat the experiment, covering the magnet with sheets of various metals in turn. We find that copper, tin, lead, zinc, wood, glass, aluminum, and various other substances do not hinder at all the passage of the magnetic force through them. The filings seem to be affected as readily as if the substances were not present. We conclude that all these substances are *transparent* to magnetism, just as glass is transparent to light. In all cases we have used non-magnetic materials.

Let us repeat the experiment, using a sheet of iron between the magnet and the filings. The iron is not transparent to magnetism. The lines of force do not *cross* the iron; they enter the iron readily and follow a path within the iron itself. Fig. 559 shows the lines of force passing across the air gap between the two poles of a horseshoe-shaped magnet. In Fig. 560, we see the

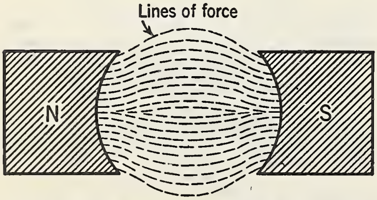


Fig. 559. Lines of force cut across the air gap.

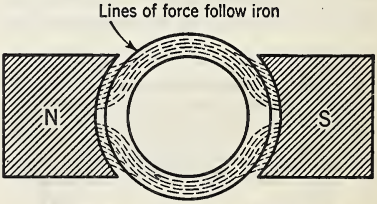


Fig. 560. Lines of force follow the soft iron ring.

effect of introducing an iron ring between the two poles. The lines of force prefer the iron to any other medium. We say that iron is very *permeable*, since it readily *gathers in* lines of force and affords an excellent path for their transmission.

**515. Is the shape of a magnet important?** We know that some magnets are straight steel bars. If we bend such a bar around until it is shaped like a horseshoe, the two poles will be rather near together. The air gap between the two poles is thus decidedly reduced. Making a magnet horseshoe-shaped concentrates the lines of force and makes the magnetic field more intense. Compare the concentration of lines of force about a bar magnet, Fig. 556, with that of the horseshoe magnet, Fig. 561*A*. When such a magnet is not in use, a small piece of steel called the *armature* is placed across the poles of the magnet, as in Fig. 561*B*. Few lines of force enter the air, because the soft steel is so permeable. Bar magnets are packed in pairs, with unlike poles adjacent. A small strip of soft iron or steel is placed across the poles at each end to afford an all-steel path for the lines of force.

**516. What is the theory of magnetism?** No one can tell what magnetism is, but the following theory seems reasonable: When we break a magnet, we do not destroy its magnetism. Even if it is broken into tiny pieces, each little bit shows polarity. It seems probable that in a piece of iron or steel the molecules themselves are tiny magnets.

In an unmagnetized bar of iron, the tiny magnet-molecules are probably all in a haphazard arrangement, as represented in Fig. 562. The small rectangles in the figure represent the molecules, and the blackened ends represent their north-seeking poles. We know that two bar magnets laid side by side with unlike poles adjacent will each nullify the effect of the other. Hence, a bar of iron in which the molecules are all in a miscellaneous grouping will have no polarity.

Now let us move a magnet along the bar, stroking it from left to right with the north-seeking pole. It attracts the south-seeking poles of the molecules, and each time we stroke the iron bar

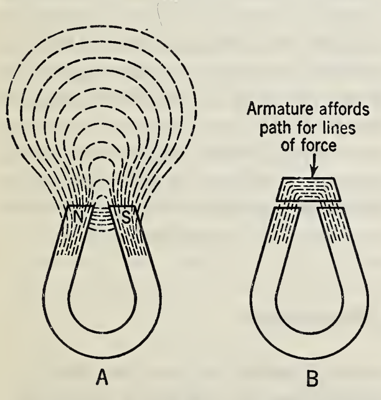


FIG. 561. *A*. Lines of force produced by a horseshoe magnet. *B*. Effect of armature.

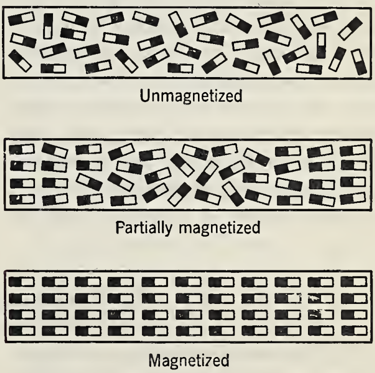


FIG. 562. *Top*. Molecules in unmagnetized bar. *Middle*. Bar is partially magnetized. *Bottom*. Bar is saturated.

with the magnet, some of the molecules will be twisted around in the bar so that they tend to arrange themselves in the position shown in Fig. 562. The bar is now *partially* magnetized, and it shows some polarity.

Suppose we continue to stroke the iron bar in the same manner. In time all the molecules will be arranged with their south-seeking poles toward the right, and their north-seeking poles at the left. The molecules will have the parallel arrangement shown in Fig. 562. The left-hand end of the newly magnetized bar will be the north-seeking pole.

**517. How do the facts support the theory?** We cannot prove that the theory of magnetism is correct, but we can make a list of several facts which furnish evidence of its correctness.

1. The theory harmonizes with the manner of making a magnet. In making the magnet, we always begin at the same end to stroke the bar. If we stroke the bar in the opposite direction, the polarity is reversed. If we stroke back and forth, we disarrange the molecules and the polarity is lost.

2. We know that heating a magnet to a red heat and pounding it removes the magnetism. The high temperature makes the molecules more *mobile*, and they swing into other positions more readily. Pounding or jarring the magnet tends to disarrange the molecules.

3. If we fill a glass tube with iron filings and stroke it carefully with one end of a bar magnet, we find that it has acquired polarity. Each filing has become a magnet by induction. If we disarrange the filings by shaking the tube, we destroy its polarity. It seems reasonable to suspect that each molecule in a piece of iron is an independent magnet.

4. The theory helps to explain induction. A magnet brought near a piece of iron pulls enough of the molecules around into an orderly arrangement to produce polarity. Most of them swing back to their former position when the magnet is removed.

5. In a piece of soft iron, the molecules are probably much more easily turned around than they are in hard steel. We know that the iron is easily magnetized, but since the molecules are more mobile, they will be more easily jostled out of their regular position. Hence, soft iron is easily magnetized and loses its magnetism easily. Steel is difficult to magnetize, but it retains its magnetism.

6. Let us magnetize a knitting needle and then heat it red hot at a spot about two inches from one end. Now if we grasp the ends with pliers and twist sharply, the needle will be distorted at the spot where it was heated. After the needle has cooled, we find that iron filings will cling not only at the ends of the needle but also on either side of the spot that had been heated. *Consequent poles* are developed in this manner by the disarrangement of the molecules at some spot in the magnet.

## 2. Terrestrial Magnetism

**518. The earth is a magnet.** William Gilbert, the physician of Queen Elizabeth, was the first Englishman to use experimental methods in order to test certain theories. As early as 1600 A.D. he published *De Magnete*, a work containing many interesting facts that he had learned by his experiments. Gilbert fashioned out of lodestone a small sphere which he called "terrella," or "little earth." When he placed small pivoted magnetic needles at different positions on this sphere, he found that their behavior was quite similar to that of magnetized needles at corresponding places on the earth's surface.

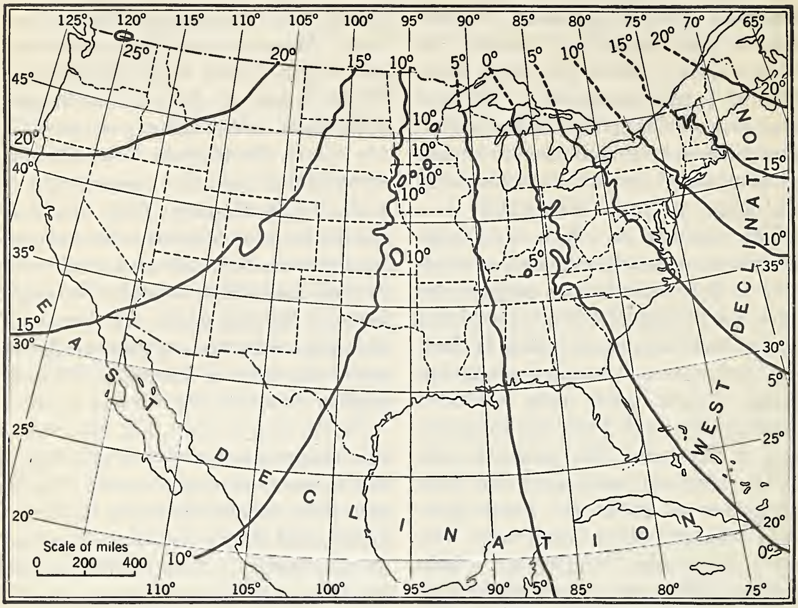
The earth in its effect upon magnetized objects and magnetic materials acts as if it were a huge magnet. Its lines of force appear to be concentrated at the earth's magnetic poles. In fact, the earth acts as it would if a large bar magnet 8000 miles long extended through the earth from one magnetic pole to the other. The magnetic pole of the northern hemisphere has been discovered at about 70° North Latitude and 96° West Longitude. The term north pole, N-pole, or + pole refers to that end of a compass needle which seeks the north. The South Magnetic Pole of the earth has been discovered at about 72° South Latitude and 155° East Longitude. The earth's lines of force may be considered *magnetic meridians* extending from one magnetic pole to the other magnetic pole.

**519. What is magnetic declination?** Columbus seems to have been the first to notice variations in the direction of the compass needle in different localities. As he sailed farther and farther west over strange seas, his compass readings seemed to become less accurate. His sailors became so thoroughly alarmed at the strange behavior of the compass needle that they threatened to mutiny and throw Columbus overboard.

If the earth's North Magnetic Pole were exactly coincident with its North Geographic Pole, then the north-seeking pole of a compass needle would always point to the *true north*. But the North Magnetic Pole is actually some 20° or about 1400 miles south of the North Geographic Pole. All north-and-south lines, or meridians, pass through the North Geographic Pole. *But the north-seeking pole of a compass points to the North Magnetic Pole.* For that reason, in most localities the compass needle varies from the true north, and we have *magnetic declination.* The angle between the true north, and the north as indicated by the compass needle, is called the *angle of declination; it is the angle of deviation from the true north.*

On the map or chart, Fig. 563, we see that there is a line of *zero declination* which passes through Canada, Michigan, Ohio, eastern Kentucky and Tennessee, and South Carolina. At places on the earth's surface through which this line passes the compass needle points to the true north. Such a line is called an *agonic* (*a*, without; *gonia*, angle) line. Lines drawn through places which have the same declination are called *isogonic* (*iso*, the same; *gonia*, angle) lines. Places east of the agonic line have *west declination*, since the compass needle points west of north. Places west of the agonic line have *east declination.*

The angle of declination varies slightly from year to year. In 1831 when the earth's North Magnetic Pole was found by Sir James Ross, it was located at 70° and 30′ N. Latitude, and 95° W. Longitude. In the year 1905 it was again located by Captain Amundsen almost 2 degrees farther west. Its position at that time was about 70° and 5′ N. Latitude, and 96° and 46′ W. Longitude. This slow westward migration of the magnetic pole causes the variation in the declination. Before a surveyor begins the survey of an unex-


125°
120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
65°
45°
40°
35°
30°
25°
20°
25°
20°
15°
10°
5°
0°
5°
10°
15°
20°
20°
15°
10°
5°
0°
EAST DECLINATION
WEST DECLINATION
Scale of miles
0 200 400
110°
105°
100°
95°
90°
85°
80°
75°

*Courtesy of U. S. Coast and Geodetic Survey*

Fig. 563. Chart of the United States, showing isogonic lines.

plored tract of land, he establishes a north-and-south line and measures the declination.

**520. What is magnetic inclination or dip?** If we place a small compass on a bar magnet and slide it along from one end to the other, near the middle it stands in a horizontal position. It dips when placed at either end of the magnet.

A compass needle mounted on a horizontal axis so that its dip may be measured is called a *dipping needle.* (See Fig. 564.) At places on the earth's surface midway between the magnetic poles, the dip is zero. A line drawn through places on the earth's surface where the dip of the needle is zero is called the *magnetic equator.* It is an *aclinic* line. Lines drawn through places having the same *dip* or *inclination* are called *isoclinic* lines. At the magnetic poles the needle stands at an angle of 90°, or in a vertical position.

**521. How can we show the inductive action of the earth?** Pieces of iron which have been lying in contact with the earth for some time usually show some signs of polarity. This is especially

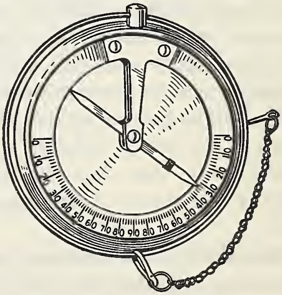

0
10
20
30
40
50
60
70
80
90
80
70
60
50
40
30
20
10
0

Fig. 564. A dipping needle. It is used to measure inclination.

likely to be true if they lie parallel to the earth's magnetic meridian. Since the earth acts as if it were a huge magnet, magnetic materials in contact with it are *magnetized by induction.* Let us hold an iron rod in the direction of the earth's meridian with the north end slanting down at an angle of about 70°. If we strike the rod a few blows with a hammer, it will when tested be found to have polarity. Now let us reverse the rod and strike it as before. When it is again tested for magnetism, the polarity is found to have been reversed. The rod may be demagnetized by holding it at right angles to the magnetic meridian (East and West) and striking it a few blows with a hammer.

## Summary

A magnet may be made by stroking a bar of steel with a lodestone, always beginning at the same end. Its magnetism may be destroyed by heating it, or by pounding it, if it is held at right angles to the magnetic meridian.

The magnetic force appears to be concentrated at or near the ends of the magnets at points called poles. The north-seeking pole of a freely swinging magnet seeks the North Magnetic Pole.

Like poles repel; unlike poles attract. A single line of force is called a maxwell. A line of force perpendicular to an area of one square centimeter gives a magnetic field of unit strength; it is called a gauss.

The earth is a huge magnet. It acts inductively upon magnetic materials near or in contact with it, magnetizing them.

The compass needle does not point to the true north at all places. The angle of deviation of the magnetic needle from the true north is called magnetic declination.

*How many of the following terms and phrases can you define or explain? (Possibly you learned some of them in General Science.)*

Natural and artificial magnets
How to make a magnet
Laws of magnets
Residual magnetism
Demagnetization
Lines of force
Transparency
Theory of magnetism
Declination
Magnetic materials
Polarity
Magnetic compass
Retentivity
Magnetic induction
Permeability
Magnetic fields
Earth is a magnet
Inclination

## QUESTIONS

1. When bar magnets are held together with unlike poles adjacent, they show little attraction for magnetic materials. When held with like poles adjacent, the attraction is increased. Explain.

2. Iron posts and pillars usually show polarity. Explain. Is the top an N-pole or an S-pole?

3. Why is polarity the best test for magnetism? Why is repulsion a surer test for magnetism than attraction?

4. If an iron bar attracts either end of a compass needle, is it magnetized? Give a reason for your answer.

5. If the balance wheel of a watch becomes magnetized, the watch fails to keep good time. How may the works of a watch be protected against magnetization?

6. Could Peary or Rear Admiral Byrd have reached the North Pole by following the direction indicated by the north-seeking pole of a compass? Explain. In what direc-

tion would the north-seeking pole of a compass point from the North Geographic Pole?

7. In an unsurveyed territory, how could you find the true north? How could you find the magnetic declination?

8. How can a dipping needle be used to indicate the presence of beds of magnetic iron ore?

9. How would you expect the declination of the compass to be affected by the presence of large beds of magnetite?

10. Why is the gyro-compass now used on submarines and many battleships?

11. When not in use, two bar magnets should be packed in a box with unlike ends adjacent, and two strips of soft iron joining the poles. Why?

12. If one pole of a bar magnet will pick up half a dozen tacks, would you expect two magnets of the same size to pick up more tacks (*a*) when the magnets are held together with like poles adjacent? (*b*) when held together with unlike poles adjacent? Make the experiment.

13. In order to pick up magnetic materials with a horseshoe-shaped magnet, the armature of the magnet must first be removed. Explain.

14. Before one begins work with magnetic needles, why should all pieces of iron be removed from the immediate vicinity?

15. From the map given in Section 519, determine what direction the north-seeking pole of a compass needle would point at (*a*) New York; (*b*) Columbus, Ohio; (*c*) St. Louis; (*d*) San Francisco.

16. Since tin is not a magnetic material, how do you account for the fact that a tin can is attracted by a magnet?

17. How would the sensitiveness of a compass needle be affected if it were enclosed in an iron case? Why is it impossible to use an ordinary compass in a submarine?

18. A ship made almost entirely of wood was sent out by the Carnegie Institute to make magnetic surveys. What are the advantages of such a ship, and why must such surveys be made from time to time?

# *Electricity — Static or Frictional*

**522. Static electricity was known to the ancients.** As long ago as the year 600 B.C., the Greek philosopher Thales is said to have discovered that a piece of amber which has been rubbed with flannel attracts small pieces of paper or pith. Nothing of value came from his discovery, and it seems to have been about 2200 years before any one discovered that *many* substances have the same property.

About 1600 A.D. William Gilbert, whose experiments on magnetism we have studied, made the discovery that different kinds of material can be excited by means of friction just as amber can. He gave the name electricity (from the Greek word for amber, *elektron*) to the phenomenon produced in this manner. He showed, too, that electricity and magnetism are not identical, although they have some properties in common.

In 1672 Otto von Guericke, whom we have already met, constructed a crude electrical machine for producing *static* (at rest) electricity. It consisted of a sphere of sulfur mounted on an axis. When the sphere was turned, the hand held against its surface was electrified.

In 1752 Benjamin Franklin performed his well-known experiment of flying a kite in a thunderstorm. He proved for us that lightning and electricity are identical, and that lightning is caused by atmospheric electricity. He also introduced the names of *positive* and *negative* for the two kinds of electricity.

**523. Electricity can be produced by friction.** No doubt you have noticed the crackling sound produced by stroking a cat's back in dry, cold weather. In winter one can shuffle around over a rug or carpet and develop enough electricity by friction to light the gas by touching the gas-jet. If your hair is dry, it flies out in all directions when you use a rubber comb, and the electrified comb will pick up bits of paper.

To detect the presence of a charge of electricity we may use a pith-ball *electroscope.* It consists merely of a ball of pith suspended from a support by means of a silk thread. If we electrify a glass rod by rubbing it with silk, and hold the electrified rod near the pith-ball, we find that it is first attracted to the rod, and then repelled. (See Fig. 565.) The same effect is produced if we rub a rod of vulcanite (hard rubber) with flannel or catskin and then hold the rod near the electroscope. It is interesting, too, to find that the silk, flannel, and catskin also show

---

## Vocabulary

ELECTROSCOPE (*elektron,* electricity; *skopos,* spy), an instrument used to detect the presence of an electric charge or of electricity.

INSULATOR, a non-conductor of electricity.

VOLT, the unit of electrical pressure.

AMPERE, the unit of current strength.

OHM, the unit of electrical resistance.

CONDUCTOR, a substance that transmits electric current.

POTENTIAL, voltage or electrical pressure.

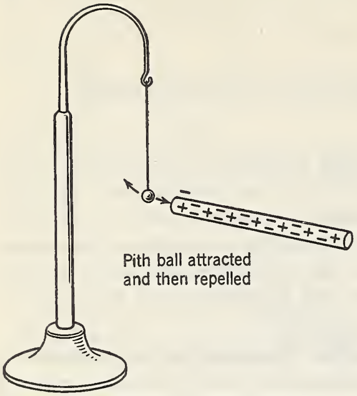


Fig. 565. A pith-ball electroscope.

signs of electrification when tested with the electroscope.

**524. There are two kinds of electricity.** Let us charge a glass rod by rubbing it with silk and then suspend it by a silk thread as shown in Fig. 566. If we bring near it a second glass rod charged in the same manner, the rods repel each other. If we bring near the suspended glass rod a piece of vulcanite which has been electrified by rubbing it with catskin, we find that the two rods attract. By the same method it can be shown that a charged vulcanite rod suspended in the same manner is repelled by a similarly charged vulcanite rod, but attracted by a glass rod electrified by rubbing it with silk. What must we conclude? It seems obvious that there are *two kinds of electricity.*

An electric charge produced on a glass rod by rubbing the rod with silk is called a *positive charge,* or *positive electricity.* That kind of an electric charge produced on a vulcanite rod by rubbing it with a piece of catskin is called a *negative charge,* or *negative electricity.* Sometimes they are called *plus* and *minus charges.* The LAW OF ELECTRIFICATION may be stated as follows: *Like electrical charges repel; unlike electrical charges attract.*

**525. What is an electroscope?** When a charged rod is brought near a pith-ball electroscope, the pith ball is first attracted to the rod, and then repelled. The charge from the rod spreads out over the pith-ball until both are charged with electricity of the same sign. Then repulsion occurs. A more sensitive electroscope is shown in Fig. 567. It consists of a brass rod terminating at one end in a brass ball or disc. The rod is thrust through a rubber stopper and suspended in a glass flask. To the lower end of the rod two strips of gold leaf or aluminum foil are attached. An electric charge applied to the ball or disc spreads down over the rod to the leaves or foil. Since both leaves are thus charged with electricity of the same sign, they repel one another.

To avoid tearing the leaves by the application of too intense a charge, a

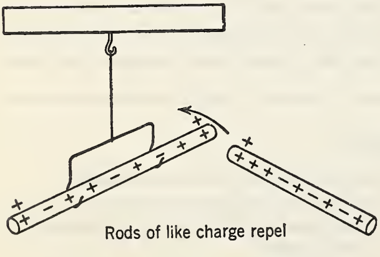


Fig. 566. Like charges repel.

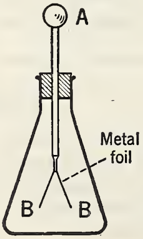


Fig. 567. A simple gold leaf electroscope. Aluminum foil is often used.

*proof-plane* is often used. Such a device may be made by cementing a penny to a rod of glass or of vulcanite. In use, the penny is first touched to the charged object and then to the knob of the electroscope. An efficient electroscope of the type shown in Fig. 568 may be used *to detect the presence of an electric charge, to determine its sign, or to measure its intensity.* Such an electroscope is used in the study of radioactive material.

**526. What are conductors and insulators?** Let us support the ball *B* of Fig. 569 by a silk thread and then join the ball to the knob of an electroscope by means of a copper wire. If the ball *B* is then charged electrically, the charge is conducted or led along the copper wire to the electroscope, whose leaves diverge. If we repeat the experiment, but connect the ball to the knob of the electroscope by means of a silk thread, any charge applied to the ball *B* does not travel to the electroscope, and there is no divergence of its leaves.

Materials which readily transmit an electric charge are called *conductors.* The metals are good conductors. Silver is the best conductor known. Copper and aluminum are also very good conductors.

Materials which do not readily conduct an electric charge are called *insulators.* Among the best insulators we find the following: mica, rubber, gutta-percha, bakelite, paraffin, shellac, oils, silk, wool, sulfur, and dry air. No conductors are perfect since even the best offer some resistance to the passage of electricity through them. On the other hand, no insulator is perfect; hence the term "conductance" is a relative one. Cotton, wood, impure water, and acids, bases, or salts in water solution are sometimes called *semi-conductors.*

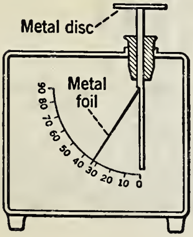


Fig. 568. An electroscope that can be used to measure the intensity of the charge.

**527. What is the theory of electricity?** The force which is called electricity has caused philosophers to wonder. We know electricity best from a study of the effects which it produces. It rings our doorbells, heats our percolators and toasters, drives our subway cars, supplies us with light, and may be used to electrocute criminals. We may mention Franklin's theory before we consider the more modern electron theory.

*Franklin's theory.* In his theory of electricity, Benjamin Franklin assumed that electricity is a *fluid.* He assumed that any object which is positively charged has an excess of electrical fluid; if an object has less electricity than normal, he considered it as negatively charged. Just as heat is believed to flow from bodies of high temperature to those of lower temperature, so Franklin assumed that electricity flows from positive (plus) to negative (minus). Al-

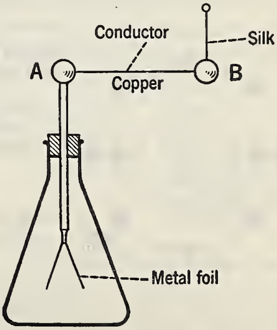


Fig. 569. Some materials conduct electricity.

though Franklin's theory is out-of-date and almost certainly incorrect, yet it was used so long that most books still use diagrams that represent electric current as flowing from the positive terminal to the negative terminal. It is nearly certain that the electric current consists of a stream of electrons which flow from the negative terminal to the positive. In the diagrams of nearly all wireless hookups the modern theory is used today.

*The electron theory.* This theory assumes that all matter consists of both positive and negative electricity. We have already discussed the theory that matter is made up of molecules and that the molecules in turn are made up of atoms. According to the electron theory, all atoms contain one or more positively charged particles called *protons.* The proton has the same weight as the lightest atom, which is the hydrogen atom. According to the Bohr theory, the nucleus of the atom always has one or more protons, and one or more neutrons. Revolving around the nucleus, as the planets revolve around the sun, are tiny particles called *electrons.* All electrons are alike, and each one is about $\frac{1}{1840}$ as heavy as the hydrogen atom. The differences in the properties of different elements is believed to depend upon the number and arrangement of the rings of planetary electrons which are revolving around the positively charged nucleus.

**528. How does the theory apply?** 1. *Chemically.* The hydrogen atom has a single planetary electron, but some of the heavy atoms have several score. In the normal atom, the sum of the negative charges of the external electrons exactly equals the charge on the positive nucleus. Such an atom is neutral, and it shows no sign of electrification. The sodium atom, represented in Fig. 570, has eleven electrons in all, two in an inner ring or sphere, eight in a second ring or sphere, and a single electron in its outer ring. The chemical symbol for sodium is Na; it is generous and may give up its outer electron. When we take an electron (−) from the sodium atom, then it becomes positively charged.

$$\mathrm{Na} - (-) = \mathrm{Na}^+.$$

It is now a sodium ion. Fig. 571 represents an atom of chlorine with seventeen electrons, seven in the outer ring. Its symbol is Cl. But the chlorine atom is greedy and may grab another electron. Then it acquires a negative charge.

$$\mathrm{Cl} + (-) = \mathrm{Cl}^-.$$

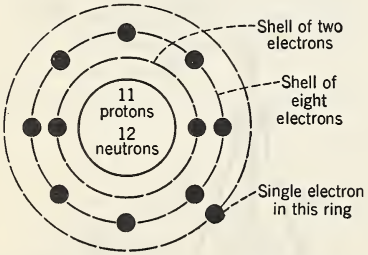


FIG. 570. The sodium atom is believed to have a single electron in its outer ring, or sphere.

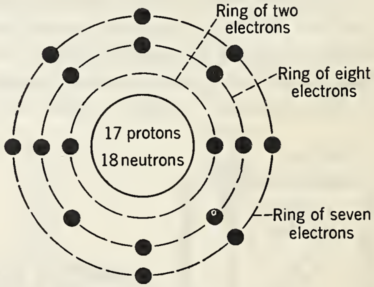


FIG. 571. The chlorine atom is believed to have seven electrons in its outer ring, or sphere.

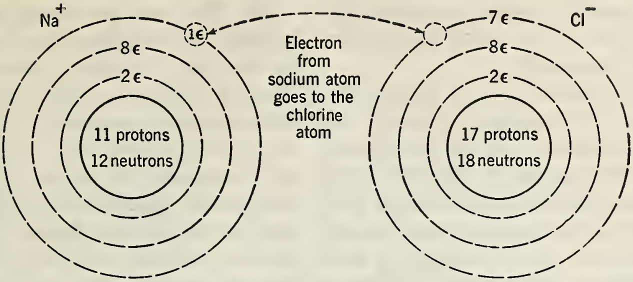

Na+
8ϵ
2ϵ
1ϵ
11 protons
12 neutrons
Electron from sodium atom goes to the chlorine atom
Cl−
7ϵ
8ϵ
2ϵ
17 protons
18 neutrons

FIG. 572. In the formation of a molecule of table salt, the positively charged sodium atom unites with the negatively charged chlorine atom.

It becomes a chlorine ion. The positive sodium ion, $Na^+$, unites with the negative chlorine ion, $Cl^-$, and forms a molecule of common table salt, NaCl. (See Fig. 572.) Chemical changes are believed to occur in such a manner.

2. *Electrically.* A glass rod is made up of protons and electrons. The protons are believed to be fixed in most cases, and the electrons to be transferable. If the numbers of electrons and protons are equal, the glass rod has *no electrical charge*: When we rub the glass rod with silk, some of the electrons leave the glass and are transferred to the silk. The glass is now *deficient in electrons;* it has a *positive charge*. The silk has an *excess of electrons;* its charge is *negative*. When we rub a vulcanite rod with catskin, electrons are transferred from the catskin to the vulcanite. Thus the vulcanite acquires a negative charge, and the catskin a positive charge. If we wrap the vulcanite rod up in the catskin and hold both near an electroscope, there is no sign of electrification. To have electrification, there must be either an *excess of electrons*, or a *deficiency of electrons.*

**529. How can we produce electrification?** 1. *By contact.* Suppose we have a negatively charged rod of vulcanite. *It has an excess of electrons.* Suppose we touch the rod with a proof plane, as shown in Fig. 573. The rod *shares* its excess electrons with the proof plane, since some of the electrons flow over to the proof plane immediately. We say that the proof plane has been charged by *conduction*, or by *contact.*

If we touch a positively charged glass rod with the proof plane, then electrons will flow from the proof plane to the glass rod to help equalize its deficiency in electrons. Both will now have a positive charge. (See Fig. 574.) *An*

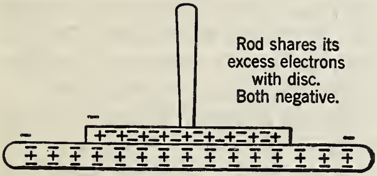

Rod shares its excess electrons with disc. Both negative.

FIG. 573. The rod shares its excess electrons with the metal disc.

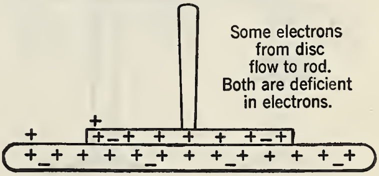

Some electrons from disc flow to rod. Both are deficient in electrons.

FIG. 574. Charging by contact. Both are of like sign.

*object charged by contact always has the same sign as the object with which it was brought into contact.*

2. *By induction.* Let us next study the effect of bringing a charged rod *near* a conductor, but *not into contact* with it. The conductor *AB* of Fig. 575 is insulated from the earth. It has just sufficient electrons to neutralize its protons. Hence it is not electrified. A rod, *C*, which has an excess of electrons (negative charges) is now brought near the conductor. Immediately the electrons are repelled to the remote end of the conductor. A charged rod brought *near* a conductor *induces* electricity of the *same sign* in the *remote* end of the conductor and it *induces* electricity of the *opposite sign* in the *near* end of the conductor. When the rod is removed, the electrons spread over the conductor as before.

When we bring a *positively* charged rod near the conductor, then the electrons are attracted to the near end of the conductor, leaving the more remote end with a deficiency of electrons. The separation of the two small pith balls beneath the conductor shows its charged condition. They fall together again when the rod is removed.

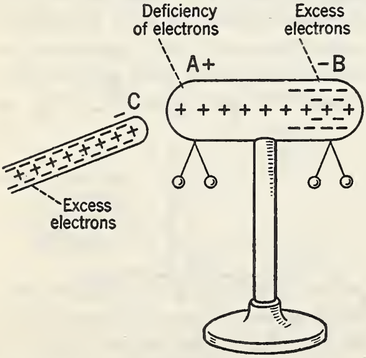


Fig. 575. Charging a rod by induction.

**530. How can we charge an electroscope by induction?** In Fig. 576*A* we have an uncharged electroscope. There is neither an excess nor a deficiency of electrons. If we hold a negatively charged rod near the knob of the electroscope, as in Fig. 576*B*, the electrons are repelled and stream away from the knob to the leaves. Thus the knob is charged positively, and the leaves negatively. The leaves diverge widely, since both are charged with the same sign. If the rod is removed, the electrons will again distribute themselves uniformly over the knob and leaves, and there will be no evidence of electrification.

Suppose, however, that we touch the knob with a finger while the rod is still held near the knob, as in Fig. 576*C*. Now the electrons will be repelled through our body, which is a fair conductor, to the earth. Since the electrons have been driven from both the knob and the leaves, they will be left with a positive charge. If the rod is removed while the finger still touches the knob, the electrons will return, and the electroscope will have no charge.

Instead of removing the rod while the finger still touches the knob, let us remove the finger *first.* The electrons were repelled to the earth through the body. The rod keeps them from coming back. (See Fig. 576*D.*) Like charges repel. After the finger has been removed, the rod may then be removed, since the electrons do not readily return through the air, which is an insulator. The electroscope is now charged with *positive* electricity, as shown in Fig. 576*E*.

We can charge an electroscope *negatively,* if we hold a charged glass rod near the knob, touch the knob, and then remove the finger before the rod is removed.

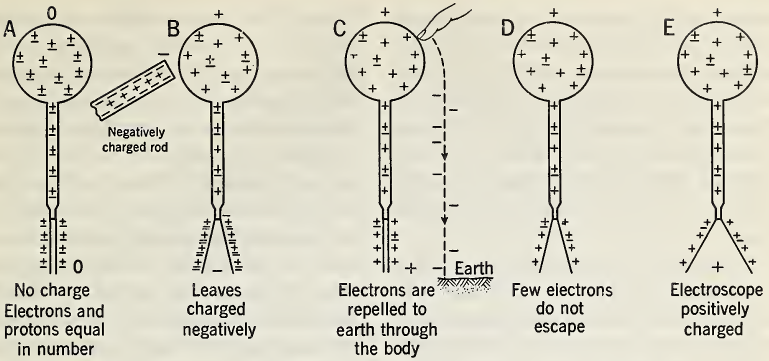

A
0
No charge
Electrons and protons equal in number
B
Negatively charged rod
Leaves charged negatively
C
Earth
Electrons are repelled to earth through the body
D
Few electrons do not escape
E
Electroscope positively charged

Fig. 576. The electroscope at *A* has no charge. It is being charged by induction at *B*. At *C*, the charge is being grounded. At *D*, the finger is removed. At *E*, the electroscope is positively charged.

A charged electroscope may be used to determine the sign of an electric charge. For example, a proof plane is touched to the object of unknown sign and then brought in contact with the knob of a *positively* charged electroscope. If the sign of the unknown body is positive, the divergence of the leaves is increased; if the sign is negative, the divergence is diminished.

**531. Where does the electric charge reside?** When the great Sir Humphry Davy was asked what he considered his greatest discovery, he replied: "Michael Faraday." We shall hear a great deal about Michael Faraday, one of the greatest scientists who ever lived. To show where the electric charge resides, Faraday used a silk bag of conical shape like that of Fig. 577. When the bag is electrically charged and then tested, it is found that the electric charge is on the *outside* of the bag. By pulling the string, the bag may be turned inside out. A further test shows that the charge is again on the outside of the bag, and that the inside shows no electrification.

A hollow sphere open at the top may also be used. The electrical charge may be applied to the inside surface of the sphere, but when both surfaces are then tested for electrification, we find that the *electric charge is on the outside of the conductor*. This is not so strange as it may seem, if we remember that the object is charged with electricity of the same sign throughout. Since like charges repel, they take up more remote positions on the outside surface.

Fig. 578 represents a hollow metal tube mounted on an insulated stand. Two pith balls are suspended from a hook placed on the outside of the cylinder, and two pith balls are hung from a loop on the inside. If the cylinder

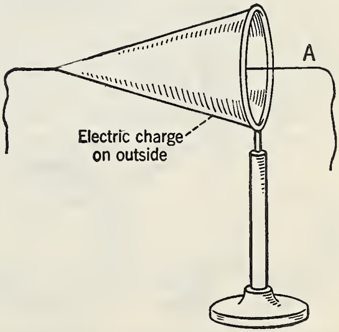

A
Electric charge on outside

Fig. 577. Faraday's experiment.

is connected by means of a chain or wire to an electrical machine, the pith balls on the outside will diverge when the machine charges the cylinder, but those inside are not affected. All these demonstrations prove that an *electric charge resides on the outside of a conductor,* or even on the outside of the silk bag.

An electroscope may be protected by surrounding it with a wire screen. Then it is not influenced by any charged objects which are brought near it, since the charge spreads over the outside of the screen, and does not affect the inside.

**532. Is the shape of the conductor important?** If we charge an egg-shaped conductor like that shown in Fig. 579 with electricity, and then test it with a proof plane, we find that all parts are not equally charged. The density is greater at the small end than at the large. If we increase the curvature by making the surface more pointed, the density will be still more increased. *The electrical density,* or *the quantity of electricity per unit area, is greatest at the point of greatest curvature.*

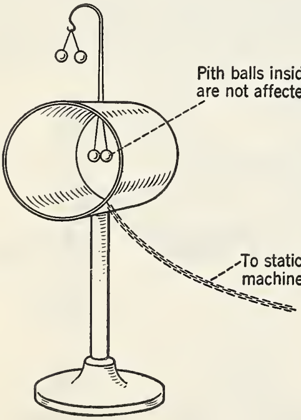


FIG. 578. The charge resides on the outside of a conductor.

**533. What is the effect of points?** Suppose we make the egg-shaped conductor of Fig. 579 still more pointed. The intensity of the charge is still more increased. As we increase the degree of curvature, the conductor becomes more and more pointed. The density of the charge becomes so great that some of the surrounding air molecules are *ionized. An ion is defined as an atom or a group of atoms that carries an electric charge.* Some molecules lose electrons and form positive ions; others gain electrons and form negative ions. Those ions which are charged with the same sign as the conductor itself are repelled with sufficient velocity to produce what is termed an *electrical wind.* Those air molecules which are charged with opposite sign from the conductor are attracted to the conductor and tend to neutralize its charge. *Hence a pointed conductor loses its charge rapidly.* Such leakage of electricity from points on the surface of a charged object is spoken of as the *discharging effect of points.*

A charged electroscope may be discharged rapidly by holding a needle a few inches from the knob. The point of the needle becomes electrified by induction, and discharges to the knob electricity of opposite sign which neu-

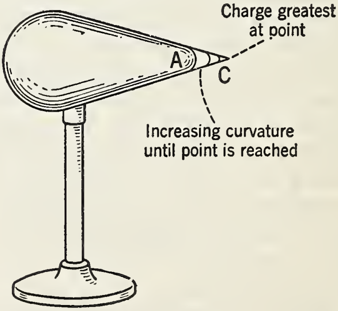


FIG. 579. How the shape of a conductor affects intensity of charge.

tralizes the charge upon the knob of the electroscope.

**534. What is electrical pressure?** We know that water flows from a tap when there is sufficient pressure to push the water out of the pipes. In a similar manner, we have learned to think of electricity as acting like a fluid. An electric charge in motion is called an *electric current*. We may think of it as a *stream of electrons flowing along a conductor*. We cannot have an electric current, however, unless the pressure at one end of the conductor is greater than it is at the opposite end. Let us carry the analogy a little further:

Given an apparatus like that shown in Fig. 580. Water poured into the left side of the apparatus exerts *pressure* against the stopcock. The pouring in of more water increases the pressure by increasing the depth. There is no current, however, because the stopcock offers too much *resistance*. If we remove most of the resistance by opening the stopcock, then water flows from $A$ to $B$ until the *back pressure* exerted by the water in arm $B$ exactly equalizes the pressure at $A$. The rate of flow must depend upon two things: (*a*) The difference in pressure between the two arms; (*b*) The size of the opening in the stopcock. The greater the difference in pressure, the faster the flow; the larger the opening in the stopcock, the faster the flow because the resistance or friction is less. We may assume that the amount of current will be *directly proportional* to the effective pressure, and *inversely proportional* to the resistance which is offered by the friction of the stopcock and pipes.

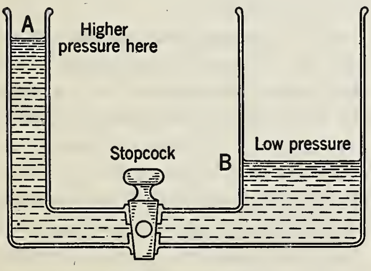


Fig. 580. Water pressure is similar to electrical pressure.

For comparison, we have two metal balls, $A$ and $B$, separated by an air gap. (See Fig. 581.) If the ball $A$ is electrically charged, pressure is exerted, similar to the water pressure at $A$ of Fig. 580. The more intense the charge, the greater the pressure. No current will flow to $B$, however, because the air gap is an insulator and acts in the same manner as the stopcock. When we join $A$ and $B$ by means of a copper wire, the resistance is decreased, and an electric current or a stream of electrons flows from $A$ to $B$ until both balls have the same electrical pressure. Here, too, the strength of the current depends upon two things: (*a*) It is directly proportional to the difference of pressure between the balls; (*b*) It is inversely proportional to the resistance of the wire.

The beginner in the study of electricity must quickly familiarize himself with three units which electricians use: (*a*) *The volt, which is the unit of electrical pressure;* (*b*) *the ampere, which is the unit of current strength;* and, (*c*) *the ohm, which is the unit of electrical resistance.* The term *electro-motive-force* (E.M.F.) is sometimes used to denote pressure.

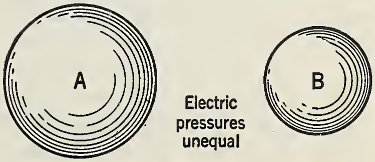


Fig. 581. The balls show a difference in electrical pressure.

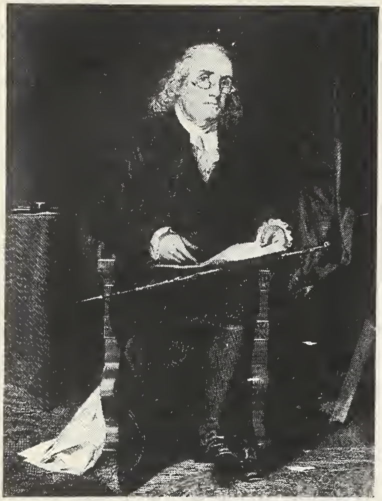


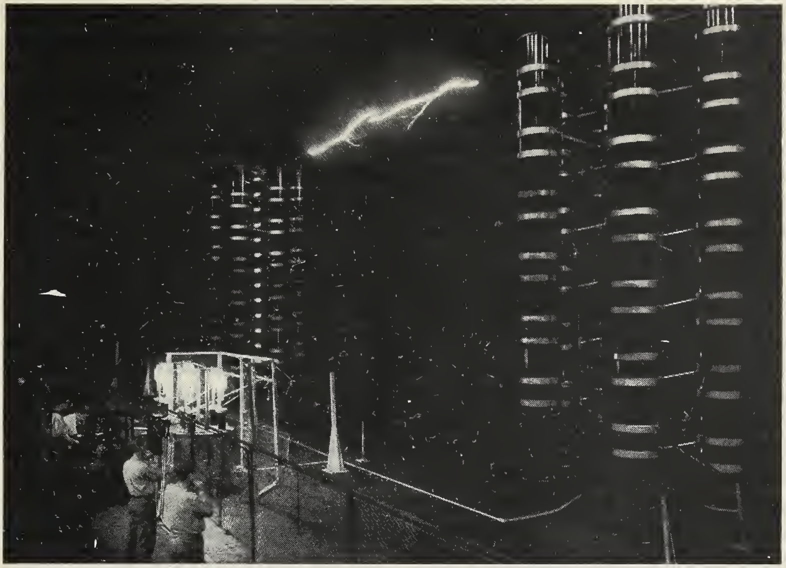
FIG. 582. Benjamin Franklin (1706–1790) was an American scientist and inventor. Every schoolboy knows the story of Franklin and his kite. He invented the lightning rod and the Franklin stove which supplanted the old fireplace.

Voltage, too, is sometimes spoken of as *electric potential.* The available pressure, or the effective pressure, is known as the *difference of potential,* abbreviated as P.D. The earth itself is considered as zero potential. Any object whose potential is higher than that of the earth is considered positive; if its potential is lower than that of the earth, it is considered negative.

**535. What may happen when we build up pressure?** It is easy to conceive that the pressure at A, Fig. 580, might be increased to such a degree that the stopcock would give way, or that leakage might occur. Likewise, it is not difficult to imagine the possibility of building up the pressure upon ball *A* until the electric charge breaks across the air gap to ball *B*. This is exactly what happens when an electric spark is produced by an electrical machine, or by stroking the fur on a cat's back. When such an electrical discharge takes place, the electricity is said to "break down the insulator, or the dielectric." Thus an insulator becomes a conductor when the voltage is sufficiently increased.

**536. What is lightning?** Every schoolboy knows the story of Benjamin Franklin and his kite. When he flew his kite in a thunderstorm and succeeded in drawing sparks from a key fastened to the string of the kite, he proved that the lightning flash and an electrical discharge of the type mentioned in Section 535 are identical. Sometimes the electrical discharge takes place between two clouds and in some cases it occurs between a cloud and the earth. A cloud may become electrically charged, possibly on account of the rapid condensation of its water vapor. If it builds up an electric potential much higher than that of the earth, then a violent electrical discharge may occur between that cloud and some object on the earth. In such a case, we say that the object has been "struck" by lightning. The air, which serves as an insulator, "breaks down" under the exceedingly high voltage, and permits the discharge to take place. In many cases, the discharge occurs between two clouds that are of different potential. (See Fig. 582.)

**537. Lightning rods furnish protection.** After Franklin had performed his well-known experiment, he invented the lightning rod for protecting buildings against lightning. A pointed rod extending above the building becomes charged inductively when a cloud passes over it, and the rod discharges the cloud quietly in much the same manner that a needle point discharges an electroscope. (See Fig. 583.)



*Courtesy of the General Electric Company*

FIG. 583. This artificial-lightning apparatus produces electricity of a very high voltage. A long spark is produced when the generator is in operation.

The statistics of fire-insurance companies show that properly installed rods are a protection, but that an improperly installed rod may be a menace. Several precautions must be taken in such installations:

1. The rod should be of a material that is a good conductor, usually copper or iron.

2. The rod must have a diameter large enough so that the rod will not be melted by the current.

3. Lightning rods should extend a short distance above the highest parts of the building, and they should terminate in several points.

4. The lower end of the rod should extend into the ground deeply enough to be always in contact with moist earth.

Opinions differ concerning the advisability of insulating the rods from the building. Both methods of installation are in use. For ordinary dwellings, it is probably better to insulate the rods to prevent lateral discharge, unless the rods run close to a waterpipe or a gaspipe. Then they should be connected with the pipes by metal conductors. Metal roofs and gutters should all be connected and then grounded.

**538. What is a condenser?** Let us connect the insulated metal plate, *A*, to an electroscope as shown in Fig. 584, and then apply a charge to the plate. As the intensity of the charge is increased, the leaves of the electroscope diverge more widely, showing that the potential is increased. Now let us bring *near* the charged plate a second plate, *B*, which is connected with the earth, or grounded. The leaves of the electroscope begin to fall together as the grounded plate is brought near the first one. The quantity of electricity has not been decreased, but the potential has been lowered. Now when we continue to add electricity to the plate $A$, we find that the *capacity* of the plate has been decidedly increased. Several times as much electricity must be added to cause the same divergence of the leaves as before, or to produce the same potential.

*A combination of conducting plates separated by insulators is known as a condenser.* In the example given, the air gap serves as the insulator. If we shove a glass plate down between the two plates, the leaves collapse to some extent, showing that the capacity is increased still more. Glass makes the insulation better. Mica is one of the best insulators for such a purpose. If we increase the size of the plates, the capacity of the condenser is increased. From our experiments, we conclude that the capacity of a condenser increases with the size of the plates, increases as the distance between the plates is decreased, and it depends upon the insulator, or the *dielectric.*

**539. How does the condenser work?** Let us suppose that the plate $A$ of Fig. 584 has a negative charge. We may keep adding to the charge. When the charge reaches a certain capacity, then electrons leak away to the air as fast as they are supplied. When the plate $B$ is brought to a position opposite to that of $A$, it becomes charged by induction. Its electrons are first repelled to the remote side of the plate and then away to the earth through the ground wire. The excess positive charges upon $B$ then hold the electrons on $A$ "bound" so that we can increase the number of electrons on $A$ many times before they increase the divergence of the leaves of the electroscope to their initial value. The unit of electrical capacity is the *farad,* but since it is such a large unit, the *micro-farad* is more often used. It has a value of one-millionth that of the farad. Condensers find extensive use in radio work.

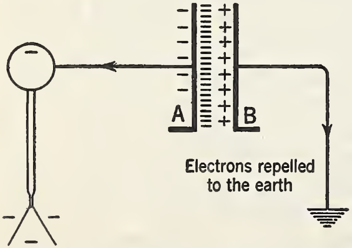


FIG. 584. The principle of the condenser.

**540. How are commercial condensers constructed?** The earliest condenser was the Leyden jar, which was made at the University of Leyden, Holland, as early as the middle of the 18th century. A glass jar is coated about halfway up, inside and outside, with tin foil. A knobbed brass rod extends through the stopper; the lower end of the rod is connected to the inner surface of the jar by a brass chain. (See Fig. 585.)

To charge a Leyden jar, we connect

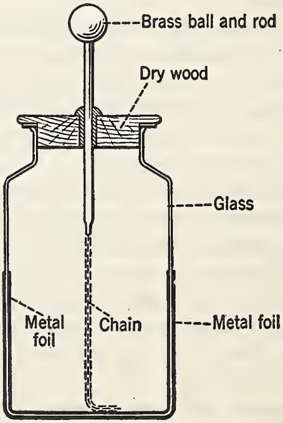


FIG. 585. The Leyden jar is a condenser.

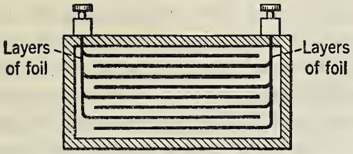


Fig. 586. A common tin-foil condenser.

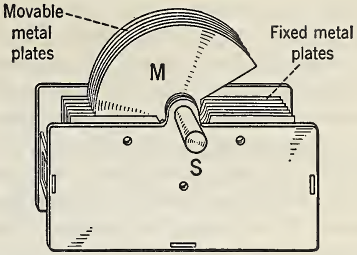


Fig. 587. The variable condenser is used in radio work.

the knob with the terminal of an electrical machine. The outer coating may be connected with the other terminal of the machine, or it may be grounded by holding the jar in the hand. In the latter case, it is connected with the earth through the human body. Thus the charge being applied to the inner surface is held "bound" by the charge of opposite sign induced upon the outer coating. The capacity of a large Leyden jar is sufficient to give quite a severe shock when the two surfaces are touched simultaneously. The jar may be discharged in this manner or by touching the knob when the jar stands on the table. It may also be discharged by placing one end of a bent conductor in contact with the outer surface and then bringing the other end close to the knob of the Leyden jar.

Condensers of the type shown in Fig. 586 are in common use. Several layers of tin foil are attached by a conductor to one binding post. To the other binding post several layers of tin foil are also connected. The layers attached to the two posts are arranged *alternately*, and they are carefully insulated from one another by layers of paraffin, oiled paper, or mica. The two binding posts are not joined by conductors at all. One of them may be positively charged and the other negatively charged.

*Variable condensers*, in which the capacity may be varied, are much used in radio sets. There are several sets of stationary metal discs, *S*, having about half of the surface of the disc cut away. Similar plates of metal are mounted on an axis in such a manner that when the axis is turned, *alternate* metal plates, *M*, slide between the fixed plates. (See Fig. 587.) The two sets of plates are insulated by the air, and they must not touch one another. As more of the surfaces of the plates overlap when we turn the axis, the capacity is increased. One of the dials of your radio set probably operates such a variable condenser.

**★541. What is an electrophorus?** Volta invented the electrophorus, shown in Fig. 588. The bed, *A*, is composed of vulcanite or some other

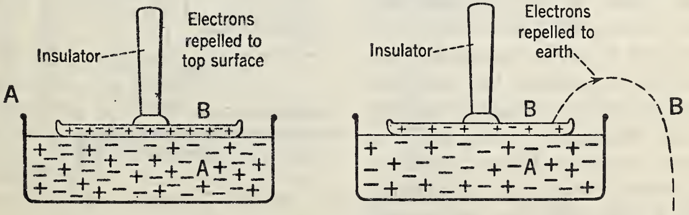

Insulator
Electrons repelled to top surface
A
B
A
Insulator
Electrons repelled to earth
B
A
B

Fig. 588. Charging an electrophorus.

insulating material. *B* is a metal disc fitted with an insulated handle. When the vulcanite bed is struck with a piece of catskin or other fur, it is negatively charged. Now if we place the disc upon the vulcanite bed, it will not be charged by contact, since it touches the surface of the insulating material at only a few points. *It is charged by induction.* The electrons are repelled to the upper surface of the disc, as shown in Fig. 588*A*. When we touch the disc with the finger, the electrons are repelled to the earth. Thus the disc becomes positively charged. (See Fig. 588*B*.)

If we lift the disc and hold a knuckle near the edge, a short electric spark may be drawn from the disc. By returning the disc to the bed, touching it a second time with the finger, and then lifting it, a spark may be obtained as before. This operation may be repeated several times without recharging the bed of vulcanite.

**★542. How do induction machines work?** Several machines that generate electricity by induction have been devised. When the terminals of the Wimshurst electrical machine are separated, this machine builds up a high potential difference. When the voltage or the pressure becomes sufficiently high, the electrical energy will break across the air gap, producing an electrical spark. To produce a spark only 1 cm. long requires a pressure of about 27,000 volts, provided the terminals are rounded and not too small. If the terminals are pointed, then only about 8000 volts are required to produce a spark 1 cm. in length. To produce the lightning flash, a tremendous voltage is required. It is not uncommon to find static or induction machines which produce a spark several inches long. While the voltage is very high, yet the current which would flow continuously if the terminals were joined, is very small. Induction machines are used for demonstration purposes in the laboratory and sometimes for operating X-ray tubes.

Cottrell devised a method of precipitating dust and smoke in factories. In the apparatus of Fig. 589, the wires are charged with high voltage. Then the dust particles, which become charged with electricity of the same sign, are repelled toward the opposite terminal. Some valuable material is recovered, and the dust nuisance is eliminated, too.

**543. Compare magnetism and electricity.** Several points of resemblance between electricity and magnetism may be noted as follows:

1. The laws of attraction and repulsion are the same in both cases.
2. Either one may be produced by induction.
3. There are magnetic fields of force and electrical fields of force.

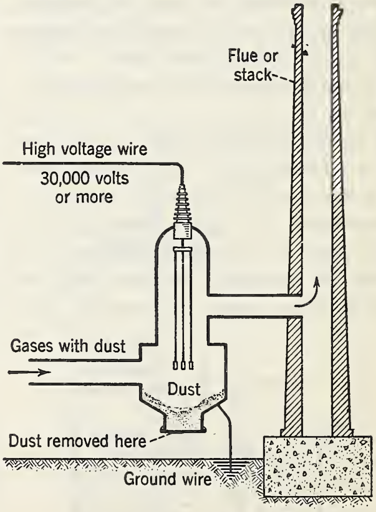


FIG. 589. The Cottrell is used to precipitate dust and smoke.

4. Magnets have plus and minus poles; there are two kinds of electricity, plus and minus. Electricity is often used to produce a magnetic effect, and magnetism is very often used to produce electrical energy.

The chief differences between magnetism and electricity are as follows:

1. Electricity may be transmitted along a conductor, but magnetism cannot be so conducted. It is difficult to insulate against magnetism, but sheet iron can be used.

2. Only a few materials can be magnetized, while any substance can be electrified.

## Summary

Electricity may be produced in any object by friction. It may also be *induced* in an object by bringing near it a charged object.

Electricity is of two kinds, positive and negative. Like charges repel; unlike charges attract.

An electroscope is used to detect the presence of an electric charge, to determine its sign, or to measure its intensity.

Conductors transmit electricity readily; insulators, or dielectrics, are poor transmitters.

The electric charge resides on the outside of a conductor. It has its greatest density where the curvature is greatest.

The volt is the unit of electrical pressure; the unit of current strength is the ampere; the unit of resistance is the ohm.

A condenser is used to increase the capacity of a conductor. The Leyden jar is a common example. Condensers, both fixed and variable, are much used in radio sets.

Lightning is a violent electrical discharge. Metal rods are often used to protect buildings against lightning.

*How many of the following terms and phrases can you define or explain?*

Electrification by friction
Electrification by contact
Effect of shape of conductor
Effect of points
Electromotive force
Condensers
Electrophorus
Electricity is of two kinds
Electron theory
Electrification by induction
Electrical pressure
Lightning
Lightning rods
Induction machines
Leyden jar

## QUESTIONS

1. How could you electrify a metal rod?

2. Why do the leaves of a pencil pad often stick together after one has been writing rapidly for some time?

3. Why do experiments with static electricity work better on clear, dry days?

4. If the little device shown in Fig. 590 is placed on a glass plate and then connected to one terminal of a static machine, the top part whirls rapidly when the machine is in operation. Explain.

5. Why should a lightning rod end in

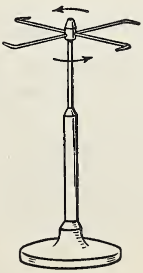


Fig. 590. The electric whirl.

several points? Why is a tall tree near a dwelling house an excellent protection against lightning?

6. Would a large wire screen put over a dwelling house be an efficient protection against lightning? Do you think that the steel frame-work of large city buildings furnishes protection?

7. Why must a proof plane have an insulated handle? Does a proof plane lose all its charge when it is touched to the knob of an electroscope?

8. Compare a magnet and a charged rod, giving as many points of similarity as you can and as many differences.

9. Is attraction or repulsion the more reliable test for electrification? Explain.

10. Why is it impossible to charge a Leyden jar appreciably if it stands on an insulator?

11. When a Leyden jar is attached to each of the terminals of a static machine, the spark produced when the discharge occurs is much thickened. Explain why the Leyden jar "fattens" the spark.

12. Is the continued use of the electrophorus an example of perpetual motion? If not, what is the source of energy?

13. Place the base of a Bunsen burner against the outer coating of a charged Leyden jar. Turn on the gas and then bring the end of the burner tube near the knob. The gas will probably be lighted. Explain.

14. Support the apparatus shown in Fig. 591 and connect it with one of the terminals of a static machine. Silk threads and brass chains are used to support the hammer and the two bells. Why do the bells ring alternately when the machine is in operation?

15. Benjamin Franklin's experiment is a dangerous one. Explain why it should not be attempted by students.

16. Explain why both kinds of electricity are produced in equal quantity at the same time.

17. Make a series of diagrams to show how you could charge an electroscope negatively.

18. What is the meaning of the term electro-motive-force? What is meant by difference of potential?

19. How does an atom differ from an ion?

20. How does the electron differ from the proton?

21. Why do you think that a lone house in the country is more likely to be "struck" by lightning than a building in the city?

22. Have you ever heard of an automobile being "struck" by lightning? Can you think of a possible reason why the inside of an automobile may be a rather safe place during a severe thunderstorm?

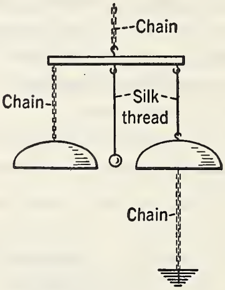


FIG. 591. The bells operate by static electricity.

# Unit Ten

# *Current Electricity*

## Preview

Any list of names of persons who have helped to develop the science of electricity would sound like a roll call in a league of nations. From Italy we have Galvani and Volta, the man who developed the voltaic cell. We honor him, too, when we use the term "volt" as the unit of electrical pressure. Everyone knows the name Marconi, who built up the transmission of radio signals and made it a commercial success.

Georg Simon Ohm was a German physicist who gave us one of the fundamental laws of electricity. In his honor, we call the unit of electrical resistance the ohm. One of the later Germans, Heinrich Hertz, was the discoverer of Hertzian waves, or radio waves. His countryman, Wilhelm Conrad Roentgen, learned how to use electricity to produce X rays.

From France we have Ampère, for whom the unit of current strength is named, and also Coulomb, who made extensive researches in electricity and magnetism and took part in the development of the metric system.

Hans Christian Oersted, a Danish physicist, paved the way for the later researches of Michael Faraday. His discovery showed the close relationship between magnetism and electricity.

When we cross the English Channel, we find such names as James Clerk-Maxwell, the mathematician, and J. J. Thomson, the man who proposed the electron theory. Of course, we must not forget the incomparable Michael Faraday, who touched so many fields in physics, but always with the hand of a master. Without Faraday's work, we might have to depend upon voltaic cells for our commercial electricity.

In the United States, our own Benjamin Franklin labeled the lightning. Joseph Henry, too, was a pioneer in his work on self-induction. He was also a leader in the practical development of the electro-magnet. In his honor, the unit of inductance is called the henry.

For lack of space, one cannot mention all the names of men who have accomplished something in this science. In the practical field, we have Thomas A. Edison, inventor of the incandescent electric lamp and a storage battery. He was a pioneer in the introduction of dynamo-electric machinery. Cyrus Field was an American who laid the first submarine Atlantic cable. In the field of communication, we also find such names as those of Samuel Morse, Alexander Graham Bell, Elisha Gray, and Lee DeForest. The list is by no means complete. It gives us only a glimpse of the many men who have helped to develop a science that can hardly be surpassed in interest or usefulness.

# *Current Electricity — Voltaic Cells*

**544. How does current electricity differ from static electricity?** Water at rest has potential energy, but it is not doing any work. When the water begins to flow, its energy becomes kinetic and it may do work. Frictional or static electricity is like water at rest. An electric charge at rest has potential energy, but it is not doing any work. An electric charge in motion has kinetic energy, and it may do work. When an electric charge moves along a conductor, we have an *electric current.*

There is no essential difference between *static* electricity and *current* electricity. The electrons streaming along a conductor form an electric current. We cannot have an electric current unless we *build up a difference of potential between two points on a conductor, or in a circuit.* Then we shall have an excess of electrons in one part of the circuit and a deficiency in another part. If the difference of potential is maintained, a *continuous current will flow through the circuit.*

Given two vertical cylinders connected near the bottom with a pipe in which there is a stopcock. (See Fig. 592.) Cylinder *A* is filled with water to the line *C*, and cylinder *B* is filled to line *D*. If we open the stopcock, water will flow from *A* to *B*, but the flow will stop as soon as the water level is the same in both cylinders. The current stops flowing when there is no longer a *difference* of pressure. It is possible to put a pump in the circuit and keep pumping water from *B* into *A* just fast enough to *maintain* the same difference of pressure as we had in the beginning. At the expense of mechanical energy, we can keep building up water pressure and maintaining a continuous flow of current, but we do not create energy.

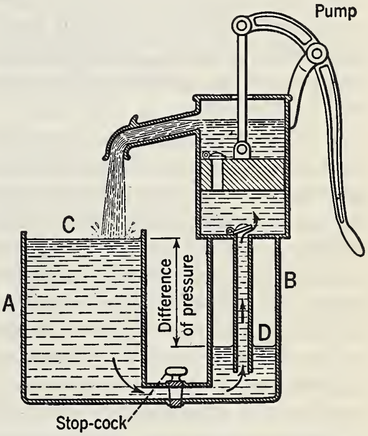


FIG. 592. The water pump maintains a constant pressure.

### Vocabulary

ION, an atom or group of atoms which carries an electrical charge.

IONIZATION, the dissociation of a chemical compound into ions.

POLARIZATION, the accumulation of hydrogen bubbles on the positive plate of a voltaic cell.

VOLTAIC, pertaining to a cell that changes chemical energy into electrical energy.

DISSOCIATE, split into ions.

MIL, one thousandth of an inch.

LOCAL ACTION, taking place within the cell itself.

CONDUCTANCE, ability to conduct current.

FIG. 593. Alessandro Volta (1745–1827) was a distinguished Italian physicist. He was the inventor of the voltaic cell. His other inventions include the electrophorus, the electroscope, and the condenser. The volt is named in his honor.

In a similar manner, if we join with a conductor two metal balls of different potential, the current will flow from the one of higher potential to the other until both have the same electrical pressure. In order to *keep the current continuous*, we must find some way to keep one of the balls constantly at a higher potential than the other. The *dynamo*, or *generator*, which is discussed later, is used for such a purpose commercially. It builds up pressure at the expense of mechanical energy. The *voltaic cell* is a simple device used to produce current electricity on a rather small scale. In such a cell, *chemical energy is sacrificed to produce electrical energy.*

**545. What is a voltaic cell?** It was in the year 1790 that Galvani made an interesting discovery. He was experimenting with a frog which was suspended by means of a copper wire attached to its leg. When the muscle of the frog's leg was touched with a scalpel, it twitched vigorously. He drew an erroneous conclusion that such twitching was due to the electricity which lay in the frog's leg. It was Alessandro Volta, another Italian physicist, who learned of Galvani's discovery and carried on a series of experiments which led to the invention of the voltaic cell. The *volt* and the *voltaic cell* are both named in his honor. (See Fig. 593.)

Let us dip a zinc rod into a water solution of some acid, sulfuric acid for example. We notice that bubbles of hydrogen gas are set free by the interaction of the zinc and the acid and that the zinc goes into solution. An electroscope test will show that the zinc rod is *negatively* charged.

Next let us dip into the acid solution a carbon rod. The acid has no effect upon the carbon rod, but if it is tested when the zinc rod is also present in the same solution, we shall find that it is *positively* charged. By the use of chemical energy, the two rods have been charged with electricity of opposite sign, and one will have a higher potential than the other.

If we connect the two rods by a conductor, an electric current flows through the wire. (See Fig. 594.) Since the chemical action goes on continu-

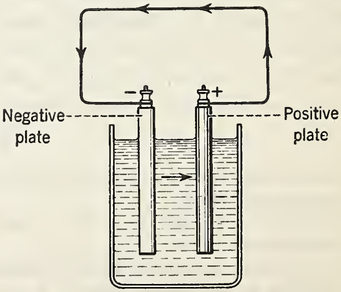


FIG. 594. Diagram of a voltaic cell.

ously, the difference of potential between the two rods is maintained, and a current continues to flow through the wire. The voltaic cell which we have just constructed is a kind of electrical pump which acts in a manner similar to that of the water pump of Section 544 in building up and maintaining a difference of pressure. *A voltaic cell consists of two dissimilar elements immersed in a fluid which acts chemically upon one of them.*

Dozens of different types of voltaic cells have been devised. For use in making the negative plate of a voltaic cell, *zinc* is the most satisfactory metal that has been found. Many different elements have been used for the positive plate, including carbon, copper, gold, silver, and even platinum. *Carbon* is the most satisfactory. Various solutions, too, have been used in different types of voltaic cells. They include such acids as sulfuric, hydrochloric, or nitric, such bases as sodium hydroxide or potassium hydroxide, and also such salts as common table salt or sal ammoniac.

**546. What are some electrical terms in common use?** Each plate of a voltaic cell is fitted with a threaded bolt and nut, called a *binding post,* to which conductors may be attached. The plate that is acted upon chemically is called the *negative plate.* There is little or no action on the *positive plate.* Joining the two plates with a conductor is called "making" or "closing" the circuit. Disconnecting the conductor is called "breaking" the circuit; the cell is then on *open circuit.* A conventional diagram is used to represent a voltaic cell. In such a diagram, Fig. 595, a long, thin line represents the positive plate, and a short, thick line the negative plate. The dotted arrow between the lines represents the solution in the cell itself.

For decades it has been customary to speak of the current as flowing from the positive plate through the *external circuit* to the negative plate. Benjamin Franklin started us off on the wrong foot. Until a Congress of Physicists meets and decides to adopt the more modern theory of electron flow, a change in any one physics textbook would lead to some confusion. With our fingers crossed, then, we shall continue to assume in the wiring diagrams that the current flows from positive to negative through the external circuit, and from negative to positive through the *internal* circuit. Pupils may feel fairly certain that the *stream of electrons* flows in the opposite direction.

**547. Here are some conventional diagrams.** Many of the pieces of electrical apparatus are so complicated that it would need an artist to make wiring diagrams if one attempted to give a real picture of them. Electricians have agreed upon the use of many conventional diagrams to represent instruments and appliances. On page 436 you will find labeled diagrams that are in common use. You will need to refer to them from time to time in your study and you should use them when you attempt to make, either for class use or in the laboratory, diagrams involving the use of such instruments.

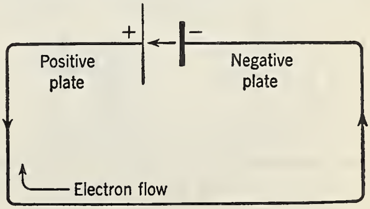


FIG. 595. Conventional diagram of a cell on closed circuit.

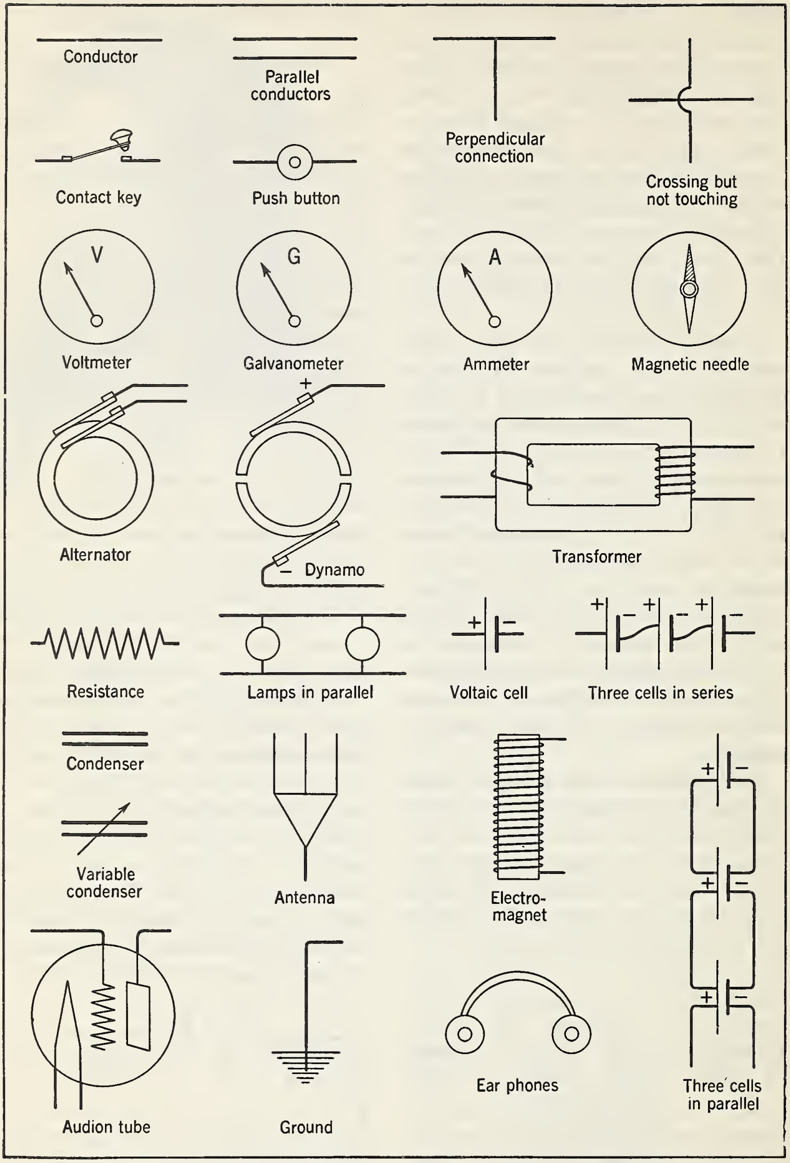

Conductor
Parallel conductors
Perpendicular connection
Crossing but not touching
Contact key
Push button
V
Voltmeter
G
Galvanometer
A
Ammeter
Magnetic needle
Alternator
+
–
Dynamo
Transformer
Resistance
Lamps in parallel
+
–
Voltaic cell
+
–
+
–
+
–
Three cells in series
Condenser
Variable condenser
Antenna
Electro-magnet
+
–
+
–
+
–
Three cells in parallel
Audion tube
Ground
Ear phones

Fig. 596. This page shows the usual conventional diagrams used by electricians.

★**548. What is the theory of action in a voltaic cell?** Suppose that we have given a simple voltaic cell in which the two elements carbon and zinc are dipped into a solution of hydrogen chloride known as hydrochloric acid. The hydrogen chloride molecule is composed of one atom of hydrogen, H, and one atom of chlorine, Cl. Its chemical formula is HCl. According to the theory of ionization proposed by Svante Arrhenius, HCl *dissociates in water solution into ions.* We know that *an ion is an atom or a group of atoms which carries an electric charge.* For example, the HCl molecule dissociates as follows:

HCl forms $H^+$ and $Cl^-$.

The hydrogen ion ($H^+$) carries a positive charge since it loses an electron. The chlorine ion ($Cl^-$) carries a negative charge, having gained an electron. Before the zinc is added, such a solution is neutral, because there are equal numbers of both kinds of charges. (See Fig. 597.)

When the zinc strip is introduced, some of the zinc atoms go into solution, forming zinc ions ($Zn^{++}$). Each zinc atom loses two electrons, thus *leaving the zinc rod or plate negatively charged.* The excess of plus zinc ions being formed around the negative plate will repel the plus hydrogen ions and drive them over toward the neutral carbon rod or plate. There, every hydrogen ion ($H^+$) takes an electron from the carbon rod, thus *leaving it charged positively.* The hydrogen ions have their charges neutralized and escape from the solution as neutral bubbles of hydrogen gas. (See Fig. 598.)

On *open circuit,* this chemical action continues until the plus charges on the carbon rod exert enough back pressure to repel the similarly charged hydrogen ions with a force exactly equal to their repulsion by the plus zinc ions. This occurs in the case of carbon and zinc when the difference of potential between the two plates of the cell is about 1.5 volts. Different combinations of elements and different solutions give somewhat different voltages. Copper and zinc, for example, give about 1.1 volts.

On *closed circuit,* there is a fall of potential along the conductor, because there is a stream of electrons from the negatively charged zinc plate flowing through the conductor and tending to neutralize the excess positive charge on the carbon rod. The chemical action is going on all the time, continuously building up a difference of potential between the two plates. It stops only when the zinc is all dissolved or the acid spent. Hence we conclude that *a voltaic cell is a device which transforms chemical energy into electrical energy.* (See Fig. 599.)

**549. What are some defects of voltaic cells?** There are two common defects of many voltaic cells: 1. Local action. 2. Polarization.

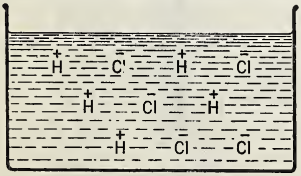


FIG. 597. The ionization of hydrogen chloride in water.

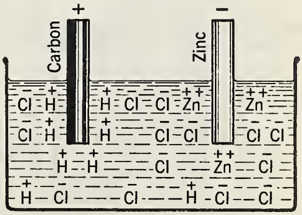


FIG. 598. Chemical action in a voltaic cell.

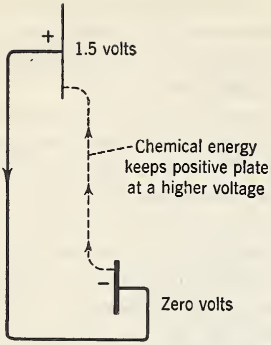


Fig. 599. A voltaic cell builds up electrical pressure.

1. *Local action.* Carbon or coal is used in extracting zinc from its ores. Hence, commercial zinc usually has some carbon particles distributed through it. As such zinc dissolves in the acid of the cell, small particles of carbon are set free. Some of the carbon particles adhere to the surface of the zinc and some remain suspended in the acid solution. Since they are not attacked by the acid, they become positively charged in just the same manner as does the positive plate. Then they set up miniature circuits within the cell itself. (See Fig. 600.) This results in a waste of energy, because such small circuits do not contribute anything to the *external circuit.* Chemical action within the cell which results only in wasted energy is called *local action.*

Local action may be remedied by the use of pure zinc, but zinc free from carbon is expensive. It was discovered in 1830 that local action can be prevented if the zinc plate is amalgamated by rubbing its surface with mercury. The mercury dissolves the zinc and brings it to the surface. The carbon impurities do not dissolve, but are kept covered and local action is prevented.

2. *Polarization.* As used here, polarization has no relation to polarization of light nor even to magnetic polarity. *It is a defect in cells caused by the accumulation of hydrogen bubbles on the positive plate.* Let us connect a simple voltaic cell with a voltmeter, as shown in Fig. 601. At first, the voltmeter will probably show a reading of about 1.5 volts. If we let such a cell *stand on closed circuit* for several minutes, we notice that the voltage gradually falls. If we examine the plates of such a cell, we find that the positive plate is covered with an accumulation of tiny bubbles of hydrogen gas. A plate of hydrogen has been virtually substituted for the carbon plate with which

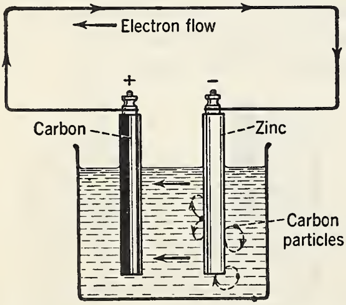


Fig. 600. Local action in a voltaic cell.

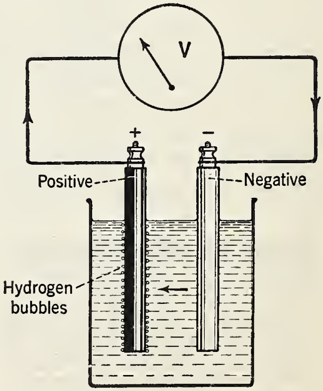


Fig. 601. Hydrogen bubbles collect on the positive plate, causing polarization.

we started. The cell is said to be *polarized.*

**550. How can polarization be prevented or remedied?** Since polarization lowers the voltage which a cell gives, it is undesirable. It also increases the internal resistance of the cell. Hence different methods have been used to prevent or remedy polarization.

1. *Mechanical.* If we lift the positive plate of a polarized cell from the solution, wipe off the hydrogen bubbles, and then put it back into the acid solution, the voltage will again rise practically to normal. Such a remedy is neither convenient nor practical, and its effect is only temporary.

2. *Chemical.* Given a polarized cell as shown in Fig. 601. If we add to it a small crystal of potassium dichromate, or some other chemical which loses its oxygen readily, we find that the voltage again rises to nearly normal. Potassium dichromate is a compound which is a vigorous *oxidizing agent.* The oxygen which it sets free combines with the hydrogen bubbles and forms water. Hence, an oxidizing agent can be used to remove hydrogen and remedy polarization. Such oxidizing agents as nitric acid, chromic acid, and manganese dioxide have been used in various types of cells to oxidize the hydrogen and prevent polarization.

3. *By construction.* Some *non-polarizing* cells have been constructed in which the hydrogen cannot reach the positive plate. In the *gravity* type, two fluids are used, one much denser than the other. The dense fluid at the bottom of the cell prevents the hydrogen from reaching the positive plate. In the *Daniell cell,* the two fluids are separated by a porous cup. It gives a constant voltage. (See laboratory exercises designed to accompany *Modern Physics.*)

**551. How is the dry cell constructed?** Of the dozens of cells that have been devised, the dry cell is now the only one that finds extensive use. The *negative plate* is a zinc cylinder which forms the walls and bottom of the cell. The *positive plate* is a carbon rod, placed in the center of the cylinder. Instead of a solution like that of the simple cell, the dry cell uses a paste made of sal ammoniac (ammonium chloride), manganese dioxide, zinc chloride, powdered coke or graphite, and a little water. The space between the carbon rod and the zinc cylinder is filled with this paste. (See Fig. 602.) The top is covered with pitch or wax to prevent loss of water by evaporation. A pin hole in the pitch or wax permits gases to escape.

The sal ammoniac is the chemical which acts upon the zinc to supply the chemical energy. The manganese dioxide is an oxidizing agent which acts as a depolarizer. The zinc chloride combines with the ammonia gas which is liberated during the chemical action and prevents its accumulation. The coke or graphite reduces the internal resistance.

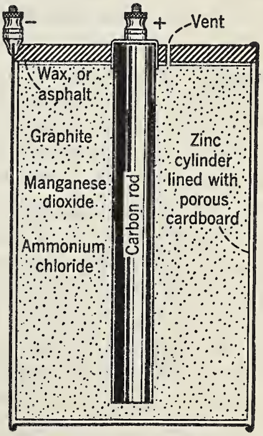


FIG. 602. Sectional view of a dry cell.

The dry cell gives an electro-motive force of about 1.5 volts. Under long, hard usage it may polarize, but it recovers when it stands on *open* circuit. Its internal resistance is so small that it may give an amperage of from 30 to 40. It may be used in any position. Dry cells are used for ringing doorbells, operating flashlights, and for other intermittent work. They find use in some portable radio sets.

**★552. What are the values of the electrical units?** We have already learned that electricians use certain units to measure electro-motive force, strength of current, and resistance. It is of interest to inquire something of the value of each of the three following units:

1. *Volt.* The volt as the unit of electrical pressure is defined in terms of the Clark standard cell, which gives a constant voltage of 1.434 when the temperature is 15° C. The Weston standard cell is sometimes used. Unfortunately for beginners, the terms electrical pressure, voltage, and electro-motive force (E.M.F.) are all used almost interchangeably. They are used as engineers use the expression "water head" to indicate water pressure.

2. *Ampere.* This unit of current strength is defined in terms of the effect that it produces. Let us connect a platinum dish with the negative terminal of a source of current of about 2 volts. We may then fill the dish partly full of a solution of some silver salt. A platinum spiral rod is connected to the positive terminal of the source of current and dipped into the silver solution. A current of one ampere flowing through such a silver solution will deposit, or plate, upon the walls of the dish 4.025 gm. of silver per hour, or 0.001118 gm. per second. This fact is used in the legal definition of the ampere. (See Fig. 603.)

3. *Ohm.* The ohm as the unit of electrical resistance represents the friction encountered by the electric current in passing through a conductor. It is defined as the amount of resistance offered by a uniform column of mercury 106.3 cm. long, and of 1 sq. mm. cross-sectional area, at a temperature of 0° C.

**553. What is Ohm's law?** The amount of water flowing through a pipe will increase with an increase in water pressure and decrease with an increase in the resistance offered by the pipe. It seems probable that the amount of current flowing in a circuit will increase with an increase in voltage, and decrease as the resistance of the circuit increases. Experiment shows that such is the case. Ohm was the first to state these observations in the form of a definite law. (See Fig. 604.) OHM'S LAW, which is one of the most important truths pertaining to electricity, may be stated as follows: *The current flowing in a circuit is directly proportional to the potential difference in volts and inversely proportional to the resistance of the circuit in ohms.* Therefore,

$$\text{current (amperes)} = \frac{\text{pressure (volts)}}{\text{resistance (ohms)}}.$$

Using the letter $I$ to represent amperes, the letter $E$ to represent difference in pressure in volts, and $R$ to

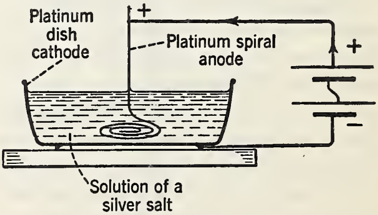


FIG. 603. The ampere is defined in terms of the rate at which it works.

represent resistance in ohms, then Ohm's law may be stated algebraically as follows:

$$I = \frac{E}{R}.$$

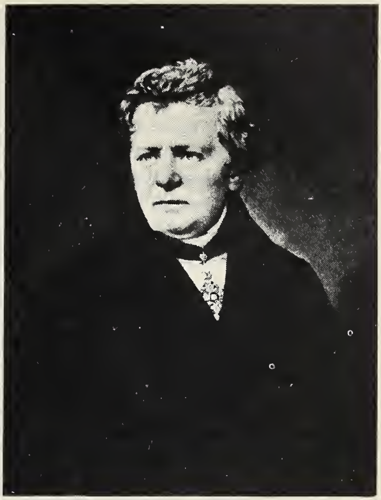
PROBLEM. In an electrical circuit, what pressure in volts is required to cause a current of 10 amperes to flow through a resistance of 4 ohms?

*Solution.* Substituting in the formula, $I = \frac{E}{R}$, we have $10 = \frac{E}{4}$. Whence, $E = 40$, the pressure in volts.

**554. What are the laws of resistance?** We have already learned that substances differ in the resistance they offer to the passage of the electric current. Some are good conductors, while others have a very high resistance. Of course, the *conductance* is inversely proportional to the *resistance*. Several factors affect the resistance.

1. *Law of lengths.* We would expect 10 ft. of waterpipe to offer 10 times as much friction to a current of water flowing through the pipe as 1 ft. By analogy, we would expect that 10 ft. of wire would have 10 times as much resistance as 1 ft. Since experiment shows that this is true, we conclude that *the resistance of a conductor is directly proportional to its length.*

2. *Law of diameters.* Everyone knows that a 6-inch pipe will carry a larger current of water than a 1-inch pipe, even if the pressure is the same in both cases. The friction encountered in trying to force water through a pin-hole opening is much greater than that which must be overcome in forcing water through a larger opening. In a similar manner, a large wire offers less resistance to a stream of electrons than a small wire does. In fact, experiment shows that a wire 1 mm. in diameter has *four times* as much resistance as a wire 2 mm. in diameter, provided both have the same length. The latter wire has four times as much cross-sectional area. Hence we conclude that *the resistance of a conductor is inversely proportional to the square of its diameter, or to its cross-sectional area.* A broad street carries more traffic than a narrow one, because it offers less resistance.



Culver Service

FIG. 604. Georg Simon Ohm (1787–1854) was a German physicist. He discovered the relation between electrical pressure, current flow, and resistance, and formulated Ohm's law. The ohm is named in his honor.

3. *Effect of temperature.* More current flows through the coils of a bread toaster when the coils are cold than after they have become heated. *The resistance of a metallic conductor increases with the temperature.* Kamerlingh Onnes found that tin and lead immersed in liquid helium (– 269° C.) have almost no resistance. At such low temperatures they became super-conductors.

The resistance of carbon, nonmetals, and the solutions of acids, bases, and salts, decreases with a rise in temperature. Glass becomes a fairly good conductor when it is heated.

4. *The resistance depends upon the material.* Copper is used more extensively as a conductor than any other metal. It offers less resistance to the passage of the current than any other metal except silver. If we let $K$ represent a *constant* depending upon the material, it is possible to summarize the LAWS OF RESISTANCE in the following formula:

$$R = \frac{Kl}{d^2};$$

$l$ is the length of the conductor in feet; $d$ is the diameter of the wire in *mils. A mil equals 0.001 inch.* Engineers sometimes use the term "circular mils" to represent the cross-sectional area of a wire. The circular mil equals the square of the diameter expressed in mils. A wire has a diameter of 0.025 in.; its diameter equals 25 mils; its cross-sectional area equals $(25)^2$, or 625 circular mils. The constant $K$ expresses the resistance in ohms of one foot of wire whose diameter is 0.001 in.; it is the resistance of one mil foot of wire. Table 15 in Appendix B gives the value of $K$ for a few of the most common conductors:

PROBLEM. Find the resistance of 150 feet of No. 24 copper wire (diameter equals 20.1 mils.)

*Solution.* We have the following data: length equals 150 ft.; $d$ equals 20.1 mils; and $K$ equals 10.38. Substituting these values in the formula,

$$R = \frac{Kl}{d^2},$$

we get

$$R = \frac{10.38 \times 150}{(20.1)^2}.$$

Whence we find $R$, the resistance, equals 3.85 ohms.

**555. Upon what does the voltage of a cell depend?** To find the answer to this question, we may connect a voltmeter to the terminals of a *non*-polarizing cell, and note the reading. If we move the plates of the cell nearer together, the voltage is not affected. If we lift one or both of the plates, the voltmeter reading remains the same as long as the plates touch the liquid. If we use a cell with smaller plates, the voltage remains the same. Hence, we conclude that the voltage of a cell does not depend upon the size of the plates, the distance between them, or the depth to which they are immersed in the solution. It can be shown by further experimentation that the *voltage of a cell depends only upon the materials used in its construction.* That refers to the metals used as plates and also to the kind of liquid used in the solution.

**556. How can we measure the resistance of a voltaic cell?** In order to measure the resistance of a voltaic cell, we need a voltmeter and an ammeter. The voltmeter, which is connected across the terminals of the cell, gives us the difference of pressure, $E$, between the two plates. (See Fig. 605.) An ammeter is connected in the cell

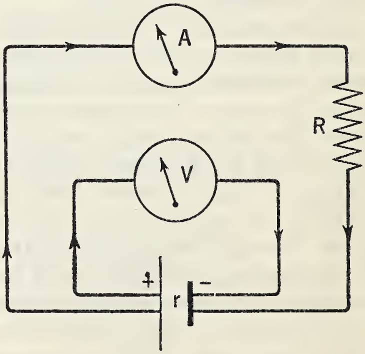


FIG. 605. How to measure the internal resistance of a cell.

circuit with a coil of resistance wire, $R$. It gives the reading, $I$, in amperes. In a cell circuit, however, we must consider two resistances: (*a*) the external resistance, $r_e$; (*b*) the internal resistance, $r_i$, offered by the solution or paste in the cell itself. The total resistance, $R$, is equal to the sum of the external resistance, $r_e$, and the internal resistance, $r_i$. Applied to a voltaic cell, Ohm's law is stated thus:

$$I = \frac{E}{r_e + r_i}.$$

The voltmeter gives us the reading $E$; the ammeter gives the reading $I$; if we use a wire of known resistance, $r_e$, then we can calculate internal resistance, $r_i$.

PROBLEM. A dry cell gives a reading of 1.5 volts; an ammeter in circuit with a coil whose resistance is 0.2 ohm shows a reading of 5 amperes. Find the internal resistance of the cell.

*Solution.* We have given the following: $E = 1.5$; $I = 5$; $r_e = 0.2$; $r_i$ is to be found. By substituting the values given in the cell formula, we get,

$$5 = \frac{1.5}{0.2 + r_i}.$$

Solving for $r_i$, we find that the internal resistance is 0.1 ohm.

**557. Voltaic cells vary in resistance.** If we measure the internal resistances of different types of cells by the method used in the preceding section, we find that they vary widely. A gravity cell or a Daniell cell will show an internal resistance of from 1 to 6 ohms. Since their voltage is only 1.1, such cells seldom furnish even one ampere of current. On the other hand, the internal resistance of a new dry cell of standard size is seldom more than 0.05 ohm, and it may be a little less. When the external resistance is zero, a cell whose voltage is 1.5 and whose resistance is 0.05 ohm can furnish 30 amperes of current.

Let us use a non-polarizing cell of the fluid type with the voltmeter and ammeter, as in Fig. 605. If we move the plates farther apart, we find that the ammeter reading drops. If we lift one or both of the plates so that they are not so deeply immersed, we again find that the ammeter reading drops. In both cases the internal resistance of the cell is increased. One might have guessed this; for, in the first case, the current must flow across a longer liquid path, and, in the second case, the cross-sectional area of the liquid path is reduced. To reduce internal resistance, *one uses large plates and places them as close together as possible.*

**558. How are cells grouped?** Sometimes a single cell does not give sufficient voltage or enough current for our needs. It is possible to group two or more cells in such a manner that we can get more voltage, more current, or both. Of the several methods used to group cells, we shall discuss only two: *series grouping, and parallel or multiple grouping.*

1. *Series grouping.* If a single tank of water does not furnish enough pressure, we can increase the "water head"

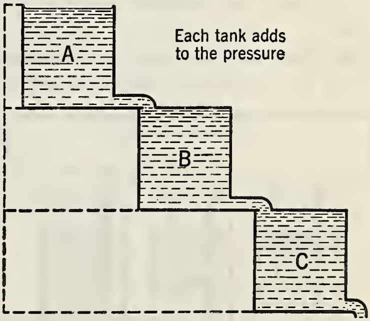


FIG. 606. Water analogy for series grouping of cells.

by placing more tanks above it, as shown in Fig. 606. Each tank increases the water pressure by increasing the depth. With three tanks, the pressure is three times as great. In a similar manner, if we group cells *in series* by joining the positive plate of one cell to the negative plate of a second, and so on, as shown in Fig. 607, we find that *each cell added increases the voltage.* If a single cell has an E.M.F. of 1.5 volts, then three cells will have an E.M.F. of 4.5 volts. When $n$ represents the number of cells, then the total voltage of $n$ cells becomes $nE$.

The water in the three tanks must flow through each of the tanks in turn; hence it meets three times as much resistance. For the same reason, the *total internal resistance* of three cells grouped in series is just three times that of a single cell. For any number of cells $n$, the internal resistance is $nr_i$. Naturally, the external resistance, $r_e$, is not affected by changes in cell grouping. For cells grouped in series, we modify the formula for Ohm's law as follows.

$$I = \frac{nE}{r_e + nr_i}.$$

Some rules which apply to cells *in series* may be formulated as follows:

(*a*) Ohm's law applies to *series* circuits.

(*b*) The *voltage* across the terminals of *all* the cells in a *series* circuit is equal to the *sum* of all the separate voltages. Hence we multiply $E$, the voltage of a single cell, by $n$, the number of cells.

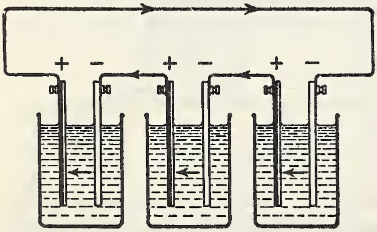


FIG. 607. How cells are grouped in series.

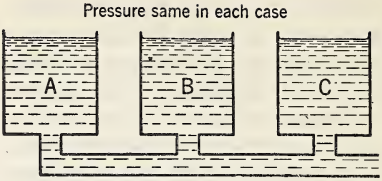


FIG. 608. Water analogy for parallel grouping.

(*c*) The total *resistance* of a *series* circuit is equal to the *sum* of all the separate resistances. Hence we multiply $r_i$, the resistance of a single cell, by $n$, the number of cells.

(*d*) The amount of *current* is the same in every part of a *series* circuit.

2. *Parallel grouping.* Suppose that we have three tanks of water all at the same level, as in Fig. 608. Connecting them all to the same external pipe does not increase the pressure. No matter how many water tanks of the

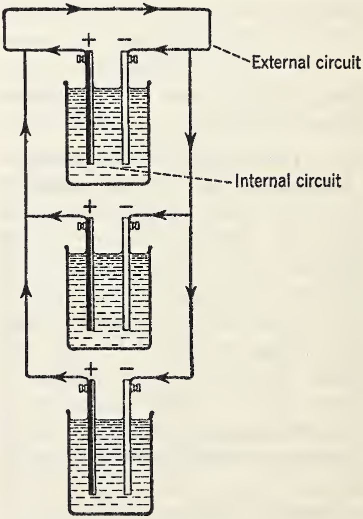


FIG. 609. How cells are grouped in parallel.

same depth we have in parallel grouping, there is no increase in pressure. In a similar manner we may group two or more cells *in parallel* by joining all the positive plates with one wire, and all the negative plates with another wire. (See Fig. 609.) In this system of grouping, *there is no increase in voltage,* no matter how many cells are used.

Since only one third of the water flows from each of the three tanks in parallel, the resistance offered is only one-third that of a single tank. In an analogous manner, one third of the current will flow through each of the three cells connected in parallel. The *total internal* resistance of three cells in parallel is only one-third that of a single cell. While grouping cells in parallel does not increase the voltage, yet in some cases we can get much more current by such grouping because the internal resistance of any number of cells, $n$, is equal to $\frac{1}{n}$ the resistance of a single cell. For parallel grouping, we modify the formula for Ohm's law as follows:

$$I = \frac{E}{r_e + \frac{r_i}{n}}.$$

The student will find it easy to understand why parallel connections decrease resistance if he stops to consider that more water can flow through two parallel pipes than through a single pipe. Two parallel roads between Detroit and Chicago offer less congestion (resistance) than a single road. If one road is closed for repairs, the traffic congestion on the other road is doubled. In a similar manner, two parallel wires offer less resistance to the passage of an electric current than either single wire.

Certain rules which apply to cells in parallel may be formulated:

(*a*) Ohm's law applies to the entire circuit or to any branch of the circuit.

(*b*) The *total voltage* across the terminals of all the cells is the same as that for a single cell. Adding cells in parallel does not raise the voltage.

(*c*) The *total internal resistance* of any number of cells in parallel is only *1-nth* of that for a single cell.

(*d*) The *total current* furnished by the group is equal to the *sum* of the currents in all the separate parts, just as each tributary adds to the volume of water in the main stream.

**559. Which grouping is better?** It is possible to test by laboratory experiments the methods of grouping cells. From the results of such experiments, the formulas used above were derived. By solving problems involving the methods of grouping cells, it is easy to find out which method gives the better results.

PROBLEM. Given 20 dry cells, voltage 1.5 each and internal resistance 0.1 ohm. What current will a single cell send through an external resistance of 500 ohms? What current will 20 cells give if they are grouped in series? What current will they produce if they are grouped in parallel?

*Solution.* (*a*) *Single cell.* By substitution in the formula for Ohm's law, we get:

$$I = \frac{1.5}{500 + 0.1}.$$

Whence, $I = 0.002999$ ampere.

(*b*) *Series.* Substituting the values given in the formula, we have:

$$I = \frac{20 \times 1.5}{500 + (20 \times 0.1)}.$$

Whence, $I = 0.059$ ampere.

(*c*) *Parallel.* Substituting in the formula for cells in parallel, we obtain the following:

$$I = \frac{1.5}{500 + \frac{0.1}{20}}.$$

Whence, $I = 0.002999$ ampere.

When we analyze the results, we

find that 20 cells in series give *nearly 20 times as much current* as a single cell does in this particular case. We observe, too, that the 20 cells in parallel give almost *the same current* as a single cell in this problem, in which the external resistance is large. But one swallow does not make a summer, and one problem does not offer conclusive proof of the merits of cell groupings. Let us try a second one.

Problem. Suppose that we have the same 20 cells to be used with a small external resistance of only 0.005 ohm. What current will a single cell furnish? What current will they produce if grouped in series? What current will flow if they are joined in parallel?

*Solution.* (*a*) *Single cell.* By substitution, we have,

$$I = \frac{1.5}{0.005 + 0.1}.$$

Whence, $I = 14.28$ amperes.

(*b*) *Series.* By substitution,

$$I = \frac{20 \times 1.5}{0.005 + (20 \times 0.1)}.$$

In this case, $I = 14.9$ amperes.

(*c*) *Parallel.* By substitution,

$$I = \frac{1.5}{0.005 + \frac{0.1}{20}}.$$

And, $I = 150$ amperes.

From a consideration of this problem, one would infer that parallel grouping is superior to series grouping, since 20 cells in series furnish only a trifle more current than a single cell. In our first problem, the external resistance was very large compared to the total internal resistance. In this problem, the external resistance was smaller than the internal resistance. If the maximum current is desired, we always use such a method of grouping cells that the *external* and *total internal resistances* are as nearly equal as possible. If the *external resistance is large, use series grouping. When the external resistance is small, use parallel grouping.* It is possible to have cells in *mixed* grouping. For example, it is possible to have two parallel groups of three cells each connected in series.

## Summary

A voltaic cell consists of two dissimilar plates immersed in a solution that acts chemically upon one of them.

Local action in a voltaic cell is caused by miniature circuits set up between carbon impurities from the zinc and the zinc plate itself. It is usually remedied by amalgamating the negative plate.

Polarization is a defect in a voltaic cell due to the accumulation of hydrogen bubbles on the positive plate. The hydrogen may be destroyed by the use of an oxidizing agent; or, by the use of some mechanical device, it may be kept from coming into contact with the positive plate.

Ohm's law is fundamental; it may be stated as follows: The current in amperes flowing in a circuit is directly proportional to the voltage and inversely proportional to the resistance in ohms.

The resistance of a conductor: (1) is directly proportional to its length; (2) depends upon the material; (3) increases with the temperature in metallic conductors; and, (4) varies inversely as the square of the diameter.

The E.M.F. of a cell depends only upon the materials used in its construction; it is independent of the size or shape of the plates, or of the distance between them.

The current a cell can furnish is directly proportional to its E.M.F.; it is inversely proportional to the internal resistance. Its internal resistance is decreased by using large plates and by placing them near together.

Cells are grouped in series or parallel. Series grouping gives the better results when the external resistance is large; parallel grouping is better when the external resistance is small compared with the internal resistance.

*How many of the following terms can you define or explain? (They are fundamental to an understanding of electricity.)*

Positive plate
External circuit
Local action
Oxidizing agent
Ohm's law
Voltage of cells
Series grouping
Negative plate
Internal circuit
Polarization
Dry cell
Laws of resistance
Resistance of cells
Parallel grouping
Non-polarizing cell

## QUESTIONS

1. Which should you use for ringing doorbells, dry cells or gravity cells? Give two reasons.

2. Make a list of the uses for which the dry cell is suitable.

3. A city is supplied with a three-foot aqueduct. It is connected to a reservoir having a capacity of one billion gallons. Do you think that the number of gallons of water that flow through the aqueduct per minute would be increased by joining to it two other reservoirs having the same level and the same capacity? From your answer explain why three cells grouped in parallel give but little more current than a single cell when the external resistance is large.

4. Why should the date of manufacture be stamped on dry cells?

5. Why is the term "dry" cell a misnomer?

6. What becomes of the energy wasted in local action?

7. Upon what factors does the voltage of a voltaic cell depend? Of what factors is it independent?

8. To renew the battery in a flashlight that contains a 6-volt bulb, how many cells does one need, and how must they be joined?

9. When would you connect cells in series? When would you join cells in parallel?

10. Why should a dry cell be kept on open circuit when not in use?

11. A dry cell may polarize from hard usage. Why does it recover when permitted to stand on open circuit?

12. How is the resistance of a wire affected by doubling its length?

13. How does doubling the diameter of a wire affect its resistance?

14. How is the resistance of a wire affected if both its length and its diameter are doubled?

15. What methods can a manufacturer of cells use to keep the internal resistance of the cell small?

16. Explain why Ohm's law is so fundamental in the study of electricity.

17. What is the advantage in the use of large plates in a voltaic cell?

18. In the dry cell the negative plate is a cylinder completely surrounding the positive plate. What is the effect upon the internal resistance of such an arrangement?

19. Why is a primary cell sometimes called a galvanic cell? Why is it often called a voltaic cell?

20. What is the meaning of the term "galvanized"? What do you infer concerning the origin of the word?

21. Could you connect enough dry cells in parallel to light a 110-volt lamp?

## PROBLEMS

### Group A

(See Table 17, Appendix B, for diameters of wires and gauge numbers.)

1. A wire 100 ft. long has a resistance of 15 ohms. What is the resistance of 200 ft. of the same wire?

2. A wire having a diameter of 0.04 in. has a resistance of 20 ohms. What is the resistance of a wire of the same length and same material, if its diameter is 0.01 in.?

3. If a wire 0.02 in. in diameter has a resistance of 2.5 ohms per 100 ft., what will be the resistance of 400 ft. of wire of the same material, if it is 0.01 in. in diameter?

4. A wire is 0.015 in. (15 mils) in diameter. It is 1500 ft. long. If it is made of copper (K = 10.38), what is its resistance?

5. What is the resistance of a wire whose dimensions are the same as those of Problem 4, if it is made of German silver (K = 181)?

6. Calculate the resistance of 25 ft. of nichrome wire (K = 660), if its gauge number is 24.

7. A wire having a resistance of 10 ohms is to be made from manganin (K = 400). If the diameter of the wire is 10 mils, what length of wire must be used?

8. An aluminum wire (K = 17.4) is 3000 feet long. Its diameter is 0.03 in. What is its resistance?

9. For the coils of a flatiron nichrome wire is used. (K = 660.) If the wire must have a resistance of 20 ohms, what must be its length when the diameter of the wire is 20 mils?

10. The flatiron of Problem 9 operates on a 120-volt circuit. How many amperes of current does it use?

11. The amount of current flowing through the hot filament of a lamp is 0.4 ampere when it operates on a 120-volt circuit. What is the resistance of the filament?

12. What current will flow in a 120-volt circuit if the total resistance of the circuit is 100 ohms?

13. What voltage is needed to send a current of 40 amperes through a resistance of 25 ohms?

14. A cell gives an E.M.F. of 2 volts. It has an internal resistance of 0.4 ohm. If it is connected to an external resistance of 0.6 ohm, what current will flow in the circuit?

15. A voltaic cell has an E.M.F. of 1.6 volts, and an internal resistance of 0.25 ohm. What is the maximum current which it can furnish when the external resistance is zero? What current can it furnish if the external resistance is 0.15 ohm?

### Group B

16. How many feet of German silver wire of gauge number 30 (K = 181) are needed to make a resistance spool of 200 ohms?

17. How many feet of No. 30 copper wire (K = 10.38) are needed to make a resistance spool of 200 ohms?

18. Compare the resistance of 1000 ft. of aluminum wire (K = 17.4) with that of 2000 ft. of copper wire (K = 10.38) if both have the same gauge number.

19. What is the resistance of one mile of No. 7 copper wire?

20. What is the resistance of one mile of No. 10 copper wire?

21. Which has the greater resistance, 2000 ft. of No. 3 aluminum wire, or 1000 ft. of No. 6 copper wire? What is the difference?

22. A piece of wire 0.2 mm. in diameter has a resistance of 1 ohm. The wire is drawn through a die which reduces its diameter to 0.1 mm. What is its resistance?

23. How many dry cells joined in series would be required to light a 120-volt lamp, if each cell has an E.M.F. of 1.5 volts? Could it be lighted by cells in parallel? Explain.

24. The maximum current which a cell furnishes is reduced exactly one half when a wire having a resistance of 0.75 ohm is joined in series with the cell. What is its internal resistance?

25. Not more than 5 amperes of current must flow through an electrical appliance which is to be used on a 120-volt circuit. Its resistance is 10 ohms. What resistance must be used in series with it to reduce the amperage to the desired amount?

26. A voltaic cell has an E.M.F. of 2 volts; its internal resistance is 0.2 ohm. What current can six such cells in series yield if the external resistance is 20 ohms?

27. What current will the six cells of Problem 26 furnish when joined in parallel?

28. What current will the six cells of Problem 26 furnish if they are joined in series and the external resistance is 0.05 ohm?

29. What current will the six cells of Problem 26 furnish if they are joined in parallel and the external resistance is 0.05 ohm?

30. A voltaic cell has an E.M.F. of 1.5 volts and an internal resistance of 0.08 ohm. What current will five such cells joined in series yield, if the external resistance is a piece of nichrome wire 3 ft. long and 15 mils in diameter? (K = 660).

# *Effects of the Electric Current*

**560. Electricity is known by its effects.** Just as a tree is known by its fruits, so electricity is known by the effects it produces. We cannot see, hear, or smell it; we know it as a form of energy. When electricity is in motion, it may produce any one of several effects:

1. When electrons are pushed through a conductor, they encounter resistance or friction and part of their energy is transformed into *heat energy.*

2. If sufficient heat is produced, the conductor may glow and produce *light energy.*

3. The electric current may be used to decompose compounds and produce a *chemical* effect. Hence it can be used to plate metals, to extract metals from their ores, and to charge storage batteries.

4. An electric current sets up a magnetic field around the conductor, and the *magnetic effects* of electricity are very important.

5. If one touches a "live" wire, his muscles will contract convulsively; electricity may produce *physiological effects.* All but the last of these effects are studied in this chapter.

## 1. Magnetic Effects

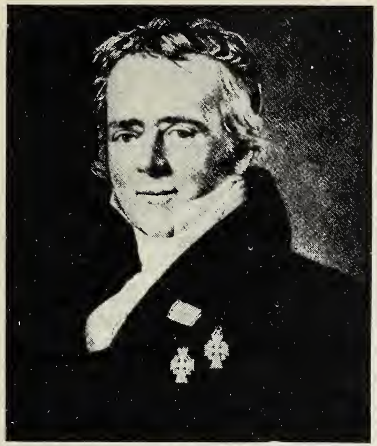
**561. Oersted's discovery.** It was in 1819 that Hans Christian Oersted, a Danish physicist, made an important discovery in the science of electricity. He found that a small compass needle is deflected when it is brought near a conductor through which a current is flowing. This fact furnishes proof of a relationship between electricity and magnetism. The mere fact that *an electric current sets up a magnetic field around the conductor through which it is flowing* may at first seem rather unimportant, but Oersted's discovery has led to some important things:

1. The development of the electromagnet is a direct outgrowth of this discovery.

---

### Vocabulary

| | |
|---|---|
| Electrolysis | the decomposition of a compound by means of the electric current. |
| Electrolyte | a compound which ionizes when melted or dissolved and thus becomes a conductor of electricity. |
| Cathode (*kata*, down; *odos*, way) | the negative terminal of an electrolytic cell, or the way by which the current leaves the cell. |
| Anode (*ana*, up; *odos*, way) | the positive terminal of an electrolytic cell, or the way by which the current enters the cell. |
| Metallurgy | the science of extracting metals from their ores. |
| Sulfation | an accumulation of lead sulfate on the plates of a storage cell. |
| Helix | a spiral coil. |
| Armature | a piece of soft iron placed across the ends of an electro-magnet. |
| Cryolite | a mineral which, when melted, will dissolve aluminum ore. |
| Nichrome | an alloy which has a high resistance and a high melting point. |



*Brown Brothers*

FIG. 610. Hans Christian Oersted (1777–1851) was a Danish physicist. In 1819 he made his famous discovery of the relationship between electricity and magnetism. This discovery paved the way for the invention of the electro-magnet and the galvanometer.

2. Many electrical instruments devised for detecting the presence of an electric current or for measuring its strength are the result of Oersted's simple discovery. (See Fig. 610.)

**562. How can one find the direction of current flow?** Suppose we repeat Oersted's experiment. We connect the terminals of a loop of wire to a voltaic cell, and place a compass needle *below* the wire when the plane of the loop is in a north-and-south line. (See Fig. 611.) When the current flows from *south to north,* the north-seeking pole of the compass needle is deflected toward the *west.* When the current is reversed, the north-seeking pole is deflected toward the east. Fig. 612 gives us a bird's-eye view of the apparatus as the deflections appear when we look downward. If one knows the direction in which the current is flowing, he can tell how the needle will be deflected. If he knows how the needle is deflected, he can tell the direction of the current. A right-hand rule has been devised to aid the student's memory.

*Right-hand rule.* 1. *If we grasp the wire with the thumb of the right hand pointing in the direction in which the current flows, the fingers beneath the wire will point in the direction in which the north-seeking pole is deflected.* Of course, the needle will be deflected in the *opposite* direction if it is placed *above* the wire carrying the current.

**563. Lines of force encircle a conductor.** From Oersted's experiments, it is evident that an electric current produces a magnetic field in which magnetic lines of force encircle the conductor. Let us pass a vertical wire

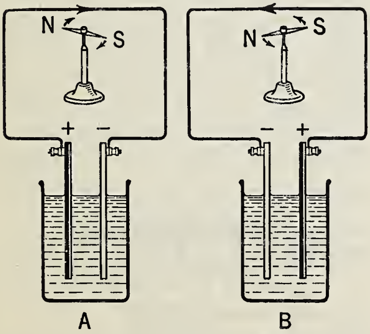


FIG. 611. Oersted's experiment proved that electricity and magnetism are related.

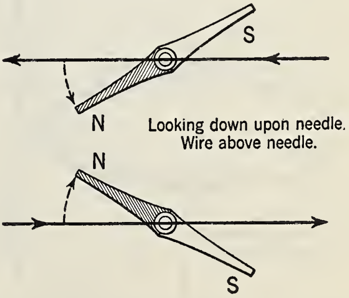


FIG. 612. Looking down upon the magnetic needles.

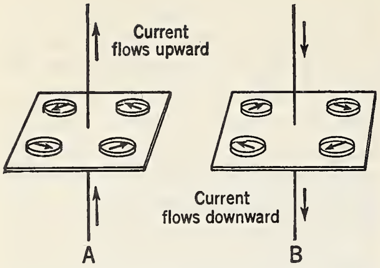


Fig. 613. The magnetic lines of force encircle the conductor.

through a cardboard and place thereon four small compasses. When a current flows through the wire, the compass needles are deflected until they become nearly tangent to the lines of force about the conductor. When the current flows *upward*, the lines of force encircle the conductor in a counter-clockwise direction, Fig. 613*A*. When the current flows *downward*, the lines of force are *clockwise*, Fig. 613*B*.

*Right-hand rule.* 2. This rule, which is not unlike 1, applies to vertical conductors. *Grasp the conductor with the right hand so that the thumb points in the direction in which the current flows; the fingers encircle the wire in the direction of the lines of force.*

**564. What is the helix or solenoid?** If we make a loop in a wire carrying a current, *the faces of the loop will show polarity*. The reason for such polarity becomes obvious, if we study the direction of the lines of force about the wire. (See Fig. 614.) Inside of the loop all the lines of force are upward, toward the north-seeking pole. On the outside of the loop all the lines of force are downward, toward the south-seeking pole. The face of the loop toward the observer becomes the *north-seeking pole* when the current flow in the loop is *counter-clockwise*. Reversing the direction of the current reverses the polarity.

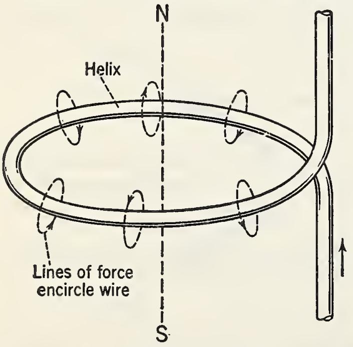


Fig. 614. A loop of wire may act as a disc magnet.

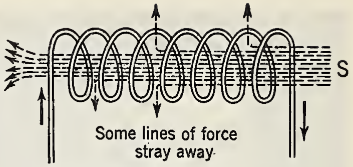


Fig. 615. The helix has polarity.

The polarity becomes much more pronounced, if we wind several such loops in the form of a spiral. (See Fig. 615.) Of course, each loop becomes a magnet, and the whole spiral then acts like a row or pile of disc magnets with their unlike poles adjacent. Such a spiral is called a *helix* or a *solenoid.*

**565. The electro-magnet.** If we refer to Fig. 615, we see that many of the lines of force tend to stray between the loops of the helix. Thus the magnetic force is scattered. To prevent such dissemination of the magnetic force, we may place an iron bar in the helix. The iron core is very permeable, and it affords an excellent path for the lines of force. (See Fig. 616.) Now we have

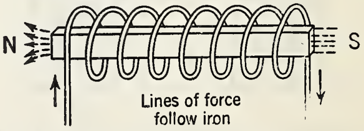


Fig. 616. The iron bar in the helix concentrates the lines of force.

an *electro-magnet*, a development from Oersted's experiment that was made practical by Joseph Henry, an American physicist.

**566. How can we make an electro-magnet?** For the core of the magnet we must select soft iron or silicon steel of great permeability so that it can be easily magnetized and demagnetized. Upon this core we wind a large number of turns of *insulated* wire. Shellac may be used to hold the wire in place. The wire must be insulated to prevent a short circuit from one coil to the adjacent one or through the iron core.

When the ends of the wire are connected to a voltaic cell, a current flows through the coils and forms a temporary magnet. When the circuit is broken, the electro-magnet loses nearly all its magnetism. The core retains a trace of what is called *residual magnetism.*

**567. How can one increase the strength of an electro-magnet?** Since each coil of wire carrying a current has its own lines of force, we can increase the strength of an electro-magnet by *increasing the number of coils or turns.* It is possible, too, to increase the strength of an electro-magnet by sending more amperes of current through the coils. Both statements may be combined to read: *The strength of an electro-magnet depends upon the number of ampere-turns.* The more permeable the core of the magnet, the more easily it is magnetized and demagnetized.

**568. How can we find the polarity of an electro-magnet?** Two methods can be used to find the polarity of an electro-magnet.

1. We may test the poles of the magnet with a compass needle. That pole which repels the north-seeking pole of the needle is of course the north-seeking pole of the magnet, and conversely.

2. We may make use of the direction of the lines of force, just as we did with the helix. This gives us a third right-hand rule.

*Right-hand magnet rule.* 3. *Grasp the magnet with the right hand with the fingers encircling the magnet in the direction in which the current flows; the extended thumb points to the north-seeking pole of the magnet.*

An electro-magnet may be horseshoe-shaped. In such a case, a coil of wire is wound around each pole of the magnet. Around one pole the wire is wound in a clockwise direction and around the other pole it is wound in a counter-clockwise direction. If we look down upon the end of such an electro-magnet at the two poles, we find that the current flowing in a *counter-clockwise* direction produces a *north-seeking* pole, and the current flowing in a *clockwise* direction produces a *south-seeking* pole. (See Fig. 617.)

**569. What uses are there for electro-magnets?** With a permanent bar magnet one can pick up a few tacks or nails, but it is possible to make electro-magnets strong enough to pick up tons of scrap iron or bars of steel. Such lifting magnets find use in loading and unloading scrap iron and steel, in handling steel billets, for lifting kegs of nails, and in manufacturing plants where heavy iron or steel machinery

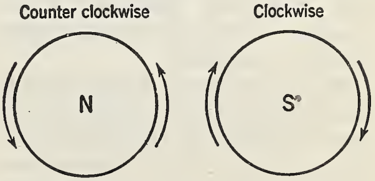
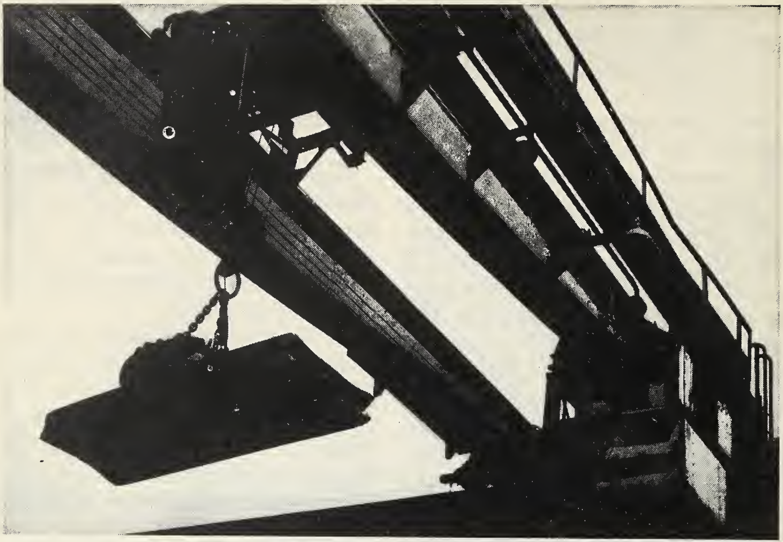


FIG. 617. Looking down upon the poles of an electro-magnet.



*Courtesy of the United States Steel Corporation*

Fig. 618. The electro-magnet is used for lifting steel and scrap iron.

has to be hoisted. Electro-magnets have been made which are so strong that they can lift a load of 200 lb. for each square inch of pole face. (See Fig. 618.)

Surgeons have used electro-magnets for removing small splinters of steel from the eye-ball or other parts of the body. We sometimes use electro-magnets to operate the drafts for the furnace.

Many electrical instruments make use of the electro-magnet. The electric bell, the telegraph, the dynamo, and the motor are important examples. Some measuring instruments, too, make use of the electro-magnet, either directly or indirectly.

**570. Of what does the electric bell consist?** Let us refer to Fig. 619 to study the parts of the electric bell. Mounted permanently upon an iron base we have a rather small electro-magnet. The ends of the wire used for the magnet windings are attached to two binding posts, *B* and *D*. The latter one is insulated from the base of the bell. Attached to the base of the

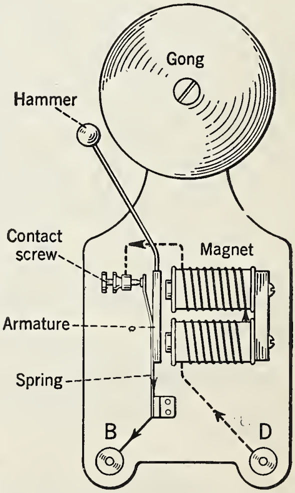


Fig. 619. Diagram of the electric bell.

bell is the spring which is bent over to make contact with the adjustable contact screw. A soft iron armature which carries the hammer is fastened to the spring. The spring is flexible, and as it vibrates back and forth the hammer strikes a series of blows upon the gong.

**571. How does the electric bell work?** Suppose we attach a voltaic cell to the binding posts, *B* and *D*, so that the current will enter the bell at *D*. It flows through the coils of the magnet to the contact screw, and then along the spring and through the iron base of the bell to *B*. As it flows through the magnet coils, it energizes the magnet, which then attracts the armature so strongly that the hammer strikes the gong. But when the armature is pulled over toward the magnet, the bent end of the spring is pulled away from the contact screw, thus breaking the circuit. The magnet then loses its magnetism and ceases to attract the armature. On account of its elasticity the spring forces the armature and hammer back to their former position. The circuit is now closed again, and the current re-magnetizes the magnet. The whole operation is repeated as before. The spring alternately "makes" and "breaks" the circuit, and the magnet is magnetized and then demagnetized in succession, thus causing the hammer to vibrate rapidly.

**572. How are bells wired?** Sometimes one wishes to have one bell in the hall and another in the kitchen, both operated by one push button. In such a case, the two bells are wired in parallel, as shown in Fig. 620*A*. When we push the button and close the circuit, the current from the battery divides, part flowing through one bell and a part through the other.

Possibly it is desirable to have one bell operated by either one of two push buttons. Then the wiring is like that shown in Fig. 620*B*. The battery must be placed between the bell and the *nearest* push button to the bell.

**573. Morse invented the telegraph.** In 1837 the inventor of the telegraph, Samuel F. B. Morse, gave a public demonstration of a telegraph by sending signals over a half-mile of wire. Six years later, Congress appropriated $30,000 to build an experimental line between Baltimore and Washington. The first message, "What hath God Wrought," was sent from Washington to Baltimore on May 24, 1844. (See Fig. 621.)

For the successful operation of a telegraph system several parts and appliances are needed. The *line wires*, the *batteries*; the *key*, the *sounder*, and the *relay* are essential parts of every system.

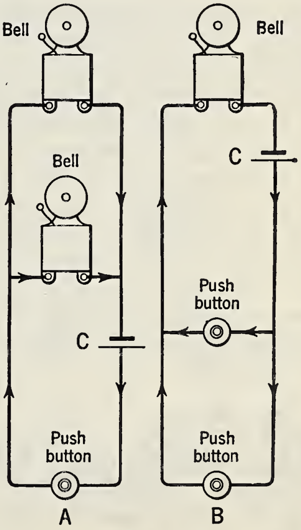


Fig. 620. *A*. Two bells wired in parallel. *B*. Two push buttons in parallel.

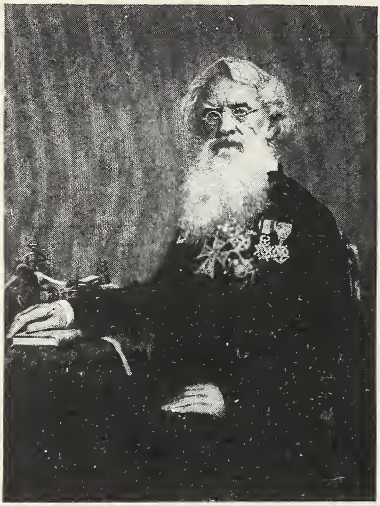


Fig. 621. Samuel F. B. Morse (1791–1872) was an American inventor. He was a Professor of Design at New York University, but gave much attention to chemistry and electricity. He is the inventor of the electric telegraph.

**574. The key is a circuit closer.** The telegraph key is used merely to open and close the circuit. The apparatus is more refined than the ordinary contact key or push button, since the contact points are made of platinum or tungsten to prevent corrosion. Thus a good contact is always assured. See Fig. 622. When the key is not in use, a lever or switch-key *S* is used to close the circuit. Unless the telegraph line is kept on closed circuit, it is impossible for one operator to call another at the farther end of the line.

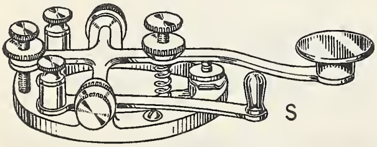


Fig. 622. A telegraph key.

**575. The sounder gives the signal.** The word *telegraph* is derived from two Greek words meaning "far" and "write," or "far-writing." In one of the early forms, a pencil was used to write the signals on a strip of paper. Now, a *sounder,* which produces an audible signal, is used. It consists of an electro-magnet mounted upon the base of the instrument. A light aluminum lever, pivoted at *A*, Fig. 623, carries an iron armature so that it is suspended a fraction of an inch above the poles of the magnet. The coiled spring keeps the lever in position. When a voltaic cell is attached to the binding posts, *B* and *C*, and the circuit closed, the electro-magnet is energized; it attracts the iron armature and pulls the lever down so that a small set screw which it carries near one end strikes the metal shoulder, *D*, with a sharp click. When the circuit is broken by the operator releasing the key, the magnet loses its magnetism and the spring then pushes the armature back away from the magnet. The operator learns to read the signals by their length and frequency, according to the Morse code.

**576. What is the Morse code?** When a telegraph key is pressed and released quickly, the sounder gives a short, sharp click known as a "dot." When the key is held for a slightly longer time, the sound is somewhat prolonged,

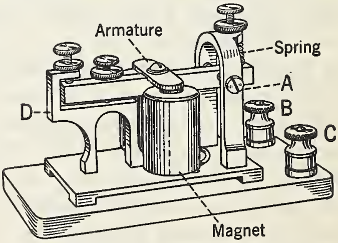


Fig. 623. A telegraph sounder.

producing what is called a "dash." Morse, the inventor of the telegraph, devised a system of dots and dashes to represent the different letters of the alphabet. It is possible to have the sounder lever carry a pencil and record the series of dots and dashes on a strip of paper, but in telegraph offices the operators read the message by ear from the clicking of the sounder.

**577. Why is a relay needed?** The line wires are usually made of galvanized iron of fairly low resistance. Such wires are strung on poles and carefully insulated to prevent grounding. Since the line may be miles and miles in length, the resistance may become great enough to reduce the current strength to a small value. It may even become so feeble that the click of the sounder is too faint to be heard easily. To prevent such a condition, a *relay* is used.

The relay serves to open and close a circuit through the sounder and a *local* battery. It consists of an electro-magnet of a large number of turns of wire. This magnet is connected to the line wires. (See Fig. 624.) When the current enters the relay through the binding posts, *A* and *B*, it energizes the electro-magnet, and by means of a pivoted armature it alternately "makes" and "breaks" the local circuit through the sounder. One end of the armature is connected to the local circuit through the binding post *C*, and the other end is connected through the binding post *D* when the end of the armature is pulled over into contact with the end of the screw. The screw has a tip of insulating material.

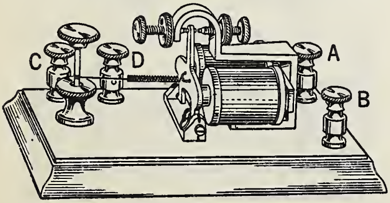


FIG. 624 The telegraphic relay.

**578. How are telegraph instruments connected?** The diagram, Fig. 625, shows how the key, sounder, and relay are connected at one end of a telegraph line. The electro-magnet of the relay is connected to the line wire through the switch or key. The line battery supplies current to the line wire. Two wires may be used, or a single wire, one end of which is grounded. The armature of the relay makes and breaks the circuit through the local battery, which operates the sounder. At the opposite end of the line the instruments are connected in the same manner.

When the operator at the *far* end of the line is sending a message, the key at the *near* end is kept closed, either by the slide lever provided for that purpose, or by the local operator himself. When the local operator is ready to send a message in reply, the operator at the far end of the line must close the key of his instrument.

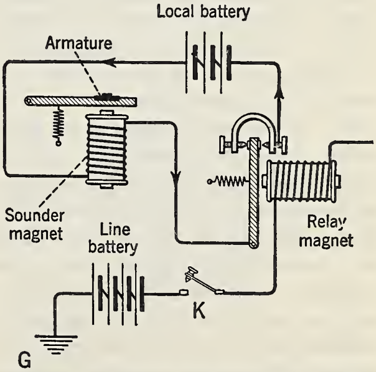


FIG. 625. Diagram of a local telegraph system, showing key, sounder, relay, and batteries.

**579. What is the teletype system?** Instead of the sounder, one may use a continuously moving roll of paper for receiving the Morse signals. As the paper moves beneath the pencil arm of the sounder lever, the dots and dashes are recorded upon it. It is possible, too, to have the message written on a machine similar to a typewriter. As the operator types the message, it is recorded automatically on a strip of paper at the other end of the line. In fact, such a message may be recorded at a large number of stations at the same time. The teletype system is extensively used by the police in sending out general alarms. It may also be used by news bureaus.

## 2. Chemical Effects

**580. What is electrolysis?** *All chemical compounds are made up of two or more elements.* From our study of the voltaic cell, we know that the compound hydrogen chloride (HCl) is made up of two elements, hydrogen (H) and chlorine (Cl). The compound known as water ($H_2O$) is made up of hydrogen and oxygen. Some compounds are broken up or decomposed by the action of sunlight; some are decomposed by the use of heat; compounds which dissolve in water or those which can be easily melted may be decomposed by the use of the *electric current.* The process is called *electrolysis* (*electro,* electricity; *luein,* to loose). Hence, we may define *electrolysis as the decomposition of a compound by means of the electric current.*

**581. What are the parts of an electrolytic cell?** The vessel or tank in which electrolysis occurs is known as an electrolytic cell. The student must distinguish between the voltaic cell and the electrolytic cell. In the former, we transform chemical into electrical energy; in the latter, electrical energy is transformed into chemical energy. The voltaic cell is often called a *primary* cell, while the electrolytic cell is known as a *secondary* cell. In the electrolytic cell of Fig. 626, we have two *electrodes.* The electrode connected to the positive terminal of some source of current is called the *anode.* Of course, the anode is positively charged. The other electrode is called the *cathode.* Since the cathode is joined to the negative terminal of a dynamo or battery, it is negatively charged. Thus the current enters the cell by way of the anode and leaves by way of the cathode. The solution or liquid through which the current flows in the cell is known as the *electrolyte.*

**582. How can we electrolyze water?** When we try to pass an electric current through pure water, we find that water is not a conductor. Hence we cannot

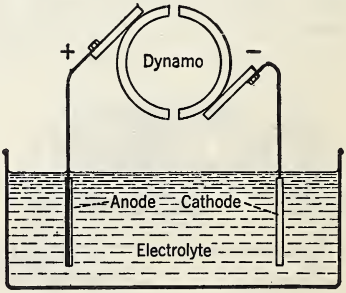


Fig. 626. A simple electrolytic cell.

decompose it *directly* by electrolysis. An *indirect* method may be used to get the same results. A little sulfuric acid added to water makes it a semiconductor. Sulfuric acid is a compound which has the chemical formula $H_2SO_4$. It is made up of hydrogen, sulfur, and oxygen. When a little sulfuric acid is added to water, some of its molecules dissociate into ions. For example,

$$H_2SO_4 \text{ forms } 2H^+ \text{ and } SO_4^=.$$

Every molecule which completely dissociates forms two hydrogen ions ($H^+$), each carrying a positive charge of electricity, and one sulfate ion ($SO_4^=$), which carries two negative charges of electricity. Suppose we put into such an *ionized* solution of sulfuric acid in water two electrodes made of platinum and connect them to the terminals of a battery or dynamo, as in Fig. 627. Since charges of unlike sign attract, the cathode will attract the hydrogen ions, and the anode will attract the sulfate ions, thus causing the ions to migrate through the solution.

When the hydrogen ions ($H^+$) reach the cathode, they take electrons from it and become bubbles of neutral hydrogen gas, which escapes from the solution. The sulfate ions ($SO_4^=$) take hydrogen from the water that is present and form sulfuric acid, thus keeping the supply of acid nearly constant. But when a sulfate ion abstracts hydrogen from water, oxygen gas is set free. Hence oxygen gas escapes at the anode, and hydrogen gas at the cathode. The water ionizes the sulfuric acid. The electric current *separates* the two ions, causing the hydrogen ions to migrate to the cathode and the sulfate ions to migrate to the anode. The following equation shows the action of the $SO_4$ group of atoms:

$$SO_4 \text{ and } H_2O \text{ form } H_2SO_4 \text{ and } O.$$

If we use an apparatus of the type shown in Fig. 628, the two gases may be collected. The hydrogen accumulates in the tube which surrounds the cathode, and the oxygen in the tube which surrounds the anode. Two volumes of hydrogen are set free for every volume of oxygen. The amount of sulfuric acid is unchanged.

A knowledge of the electrolysis of water is important for the student who wishes to understand the chemical action in a storage cell when it is being charged and while it is discharging. Both hydrogen and oxygen have many industrial uses. One of the commercial

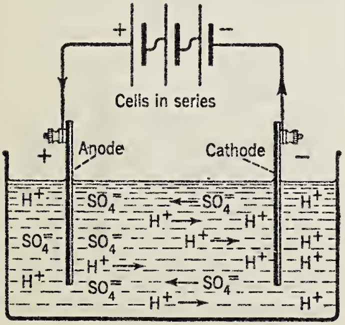


FIG. 627. A diagram to show how sulfuric acid ionizes.

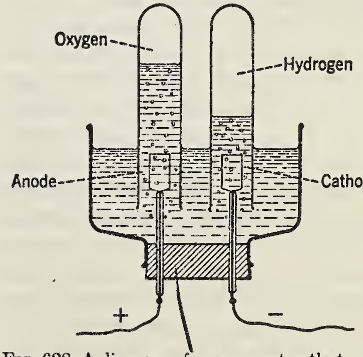


FIG. 628. A diagram of an apparatus that may be used for the electrolysis of water.

methods of preparing them is by the electrolysis of water.

**583. How are metals plated?** Our most useful metal, iron, rusts rapidly when exposed to moist air. It may be painted with powdered aluminum to give it a protective covering. It may be galvanized by dipping it into molten zinc, or tinned by dipping it into a bath of molten tin. It may be coated with copper, nickel, or chromium by a process called *electro-plating*. Some of the baser metals are also plated with such metals as silver, gold, chromium, or rhodium to improve their appearance.

Suppose we use the method of copper plating to illustrate the process. The plating is carried on in an electrolytic cell or vat. The electrolyte used is copper sulfate, which has the formula $CuSO_4$. We note that each molecule of copper sulfate is made up of one atom of copper, Cu, one of sulfur, and four atoms of oxygen. When it dissolves in water, it dissociates into copper ions ($Cu^{++}$), each of which carries two positive charges, and sulfate ions ($SO_4^=$), each carrying two negative charges. *The object to be plated is suspended from the cathode.* For the *anode we use a bar of pure copper.* (See Fig. 629.)

When the current from a battery or dynamo is turned on, the copper ions are attracted to the cathode where they take on electrons and become copper atoms. The copper atoms do not escape, however, as the hydrogen does in the electrolysis of water, but they are deposited in an even layer upon the object to be plated. The sulfate ions migrate to the anode, where their charge is neutralized. Then each one takes two electrons from a copper atom of the anode, causing it to go into solution as a copper ion with two positive charges. This action keeps the concentration of copper ions in the electrolyte nearly constant.

If we wish to plate an object with silver, we attach it to the cathode and use a bar of pure silver as the anode. Some salt of silver is used as the electrolyte. The action is similar to that which occurs during the plating with copper. The positively charged silver ions migrate to the cathode where they gain electrons and are deposited as metallic silver.

In general, *the object to be plated is made the cathode; a bar of the pure metal with which the object is to be plated is made the anode; a salt of the metal is used as the electrolyte.* The metal plating adheres better if a relatively small current is used during the plating. When the amperage is too high, the metal plate will be crystalline, and it will scale off. More amperage may be used to hasten the process if the electrolyte is stirred or agitated. This may be done by a mechanical stirrer, or by rotating either the anode or the cathode. Thus the ions are kept evenly distributed.

**584. How are electrotypes made?** The type for newspapers is usually set

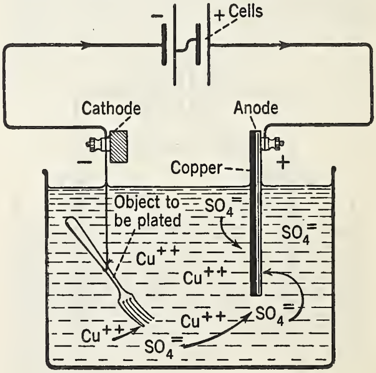


FIG. 629. How a cell may be wired for electroplating.

on linotype machines. After the paper is printed, the type is melted to be used over again. If a person wishes the same advertisement used in several papers or magazines, or in several successive issues of the same magazine, he may have the type set just once, and then have as many electrotypes made and sent to various printers as he wishes. Thus he saves labor costs.

In the making of an electrotype, the type page may be set in the usual way, by hand or by machine. Then an impression of the type page is made by covering it with a special wax which is pressed down into the type to fill all the depressions. The wax is then removed and the face of it is covered with graphite in order to make it a conductor. Next it is attached to the cathode of a copper-plating cell. When a firm layer of copper has been deposited by electrolysis, the electrotype is removed from the plating solution. The wax is melted away and the copper sheet is backed with tin foil and enough cheap metal to make it so thick and rigid that it will not bend in the printing press. To lengthen its life, the electrotype may be plated with nickel to increase its hardness.

From plates or electrotypes made in this manner, publishers may print a few thousand copies of a book, and then store the plates until the first printing has been sold. It takes only a short time to put the plates in a press and print more copies as needed. (See Fig. 630.)

Thousands of phonograph records are made from one master record which is an electrotype made from the original record. Facsimile reproductions of chased ornaments and of other works of art are often made by means of *electrotyping.*

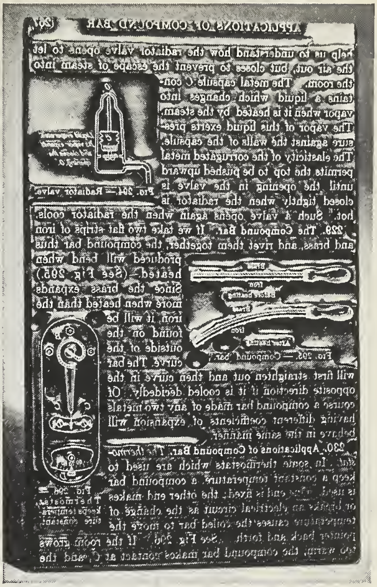


FIG. 630. An electrotype used for printing page 267 of *Modern Physics*, 1934 Edition. There have been over 250,000 impressions taken from this plate.

**585. How are metals extracted?** In one of his lectures, Professor Jewett, of Oberlin College, made the following remark: "Any person who discovers a process by which aluminum can be made on a commercial scale will bless humanity and make a fortune for himself." As the students left the room, Charles Martin Hall remarked to a classmate, "I'm going for that metal." Hall borrowed some voltaic cells from Professor Jewett and from the physics laboratory of the college and set up a laboratory in his woodshed. Two years later he handed to Professor Jewett a lump of aluminum that he had extracted by electrolysis. At that time, in 1886, aluminum cost about $8.00 per pound.

Many metals are extracted from their ores by heating the ores with

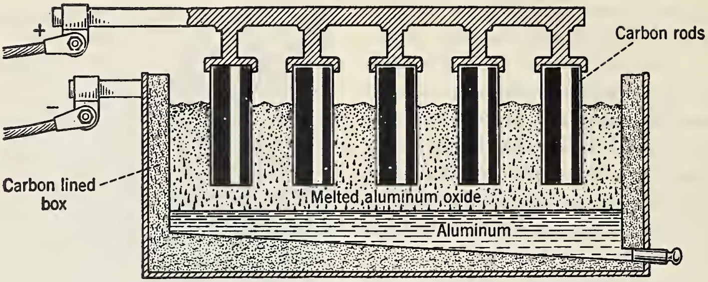


FIG. 631. Apparatus used for electrolysis of aluminum oxide.

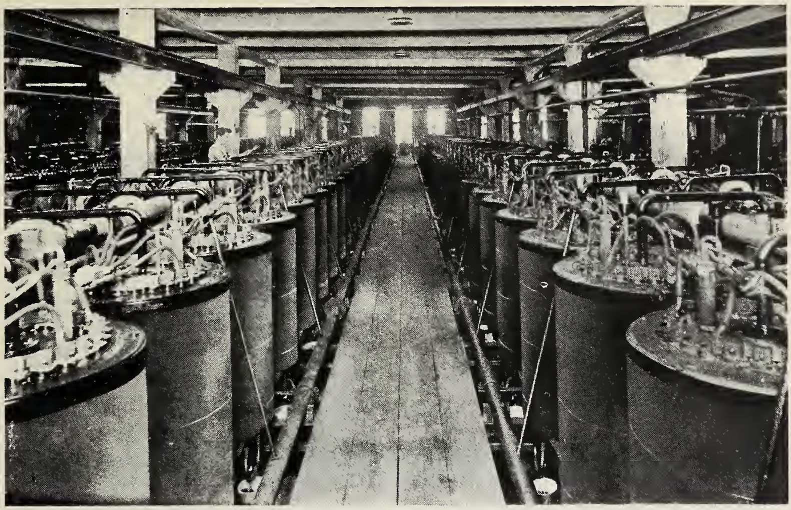
coke or carbon. This method does not work with aluminum. The chief ore of aluminum is bauxite, which consists largely of aluminum oxide, $Al_2O_3$. Before the oxide can be decomposed by electrolysis, it must be either melted or dissolved to ionize it. Since its melting point is about 2000° C., and it does not dissolve in water, Hall had to look for a solvent. He found that aluminum oxide will ionize in melted cryolite, a mineral found in Greenland.

In the Hall process, an iron box is made the cathode. (See Fig. 631.) The anode consists of several carbon rods which dip down into the electrolyte, a solution of aluminum oxide in melted cryolite. The negative oxygen ions migrate to the carbon rods. The aluminum ions migrate to the cathode where they are neutralized to form atoms of aluminum. The molten aluminum collects in the bottom of the box, whence it is tapped off from time to time. This process, known as *electro-metallurgy*, is carried on at Niagara Falls where electrical energy is inexpensive. The Hall process, which reduced the price of aluminum to about 20 cents per pound, proved so successful that when he died in 1914, he left several million dollars, a part of the estate he acquired through his discovery, to Oberlin College.

Other metals, such as sodium, magnesium, and potassium, are *extracted* from their ores by electrolysis. The non-metal chlorine is also prepared by the same method. Early in the year 1918, a plant built at Edgewood, Maryland, for making poison gases had a capacity of over 100 tons of chlorine per day. As a general rule, metals collect at the cathode, and non-metals at the anode. (See Fig. 632.)

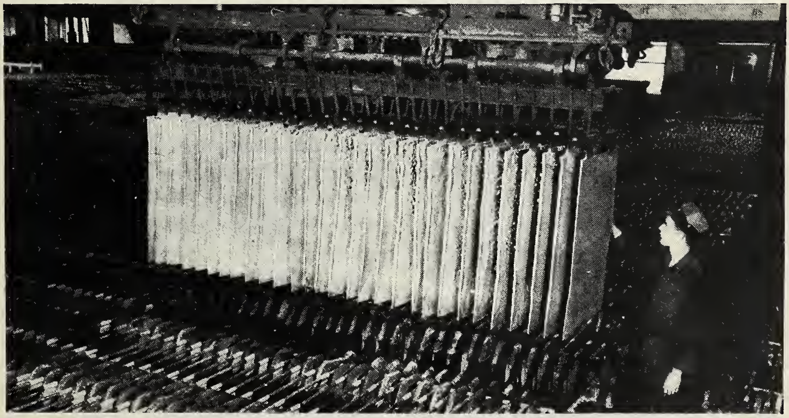
Certain metals are *refined* by electrolysis. Copper, for example, is purified by using a bar of impure copper as the anode of an electrolytic cell, and a thin sheet of very pure copper as the cathode. When the current is turned on, the impure copper goes into solution at the anode, and highly refined copper is plated upon the cathode. The impurities collect at the bottom of the tank as a kind of "mud," from which gold and silver, which are often found in small quantities in copper ores, are recovered. They are separated from each other, and may be refined by electrolysis. (See Fig. 633.) Tin is purified by electrolysis in a similar manner to that used for refining copper.

Copper which is to be used for electrical purposes must be *very pure.* Small traces of arsenic or antimony present in copper will nearly double its resistance to the passage of an electric current. The presence of only 0.4% of



*Courtesy of the Electro Bleaching Gas Company*

FIG. 632. Preparation of chlorine by means of electrolysis. Chlorine is set free in these large cells and forced under pressure into steel cylinders. The chlorine liquefies and is marketed in this manner.



*Courtesy of the Anaconda Copper Mining Company*

FIG. 633. View of the tankhouse in which copper is refined by electrolysis. Note the enormous size of the building and the huge number of electrolytic cells. In the foreground we see one set of anodes and cathodes lifted from their electrolytic cell. In some cases, the gold and silver which are recovered during the refining of copper are valuable enough to pay the expenses of the refining process.

iron in a copper wire lowers its conductivity 64%.

**586. What are the laws of electrolysis?** We have already met Michael Faraday, the poor boy who was so much impressed by one of the lectures given by Sir Humphry Davy that he approached him after the lecture and asked permission to work in his laboratory. As Davy's assistant, he learned how to liquefy gases, he formulated the laws of electrolysis and finally discovered the principle upon which the operation of the dynamo is based.

Faraday formulated three LAWS OF ELECTROLYSIS. He found that a current that deposits half a pennyweight of silver in ten minutes will deposit one pennyweight of silver in twenty minutes. In general, we may say:

LAW 1. *The amount of any metal that is deposited by an electric current is directly proportional to the length of time the current flows.*

From experiment it was shown that a current of one ampere will deposit by electrolysis exactly 0.001118 gm. of silver per second, and that a current of ten amperes will deposit exactly ten times as much per second. The law is so exact that the ampere is legally defined in terms of the amount of silver deposited per second. Stated in general terms:

LAW 2. *The amount of any metal deposited during electrolysis is directly proportional to the strength of the current in amperes.*

Some elements are deposited by electrolysis much faster than others. For example, that current which will liberate 1 gm. of hydrogen can in the same time liberate 8 gm. of oxygen, or 35.5 gm. of chlorine. The same current that will deposit 107.88 gm. of silver in a given time will deposit 31.8 gm. of copper, or only 9 gm. of aluminum in the same time. We see that 1 gm. of the element hydrogen is equivalent to 8 gm. of oxygen, to 9 gm. of aluminum, or to 107.88 gm. of silver. The law may be stated as follows:

LAW 3. *The amount of an element deposited in a given time by a current of one ampere is directly proportional to the electro-chemical equivalent of the element.*

**587. What is the principle of the storage cell?** In our study of the voltaic cell, we found that two *dissimilar elements* immersed in a fluid that acts chemically upon one of them may be used to produce an *electric current.* Such a *primary* cell transforms chemical energy into electrical energy. It is also possible to start with two plates more or less *similar* and make them *dissimilar* by means of electrolysis. Thus we use the electric current *to store up chemical energy,* or to transform electrical energy into chemical energy. Such a *storage cell,* or secondary cell, may then be used just like a voltaic cell to produce an electric current. When the storage cell is *being charged,* it utilizes the electrical current. As it is *being discharged,* the stored chemical energy is utilized to produce an electric current.

**588. How does the lead storage cell work?** Let us immerse two lead plates in a water solution of sulfuric acid. When these two plates are connected to the terminals of a direct current dynamo or a few cells in series, the electric current decomposes the water indirectly in a manner just like that described in Section 582. The hydrogen escapes at the cathode, but the oxygen does not escape when *lead plates* are used. (See Fig. 634.) The oxygen unites chemically with the lead anode to form lead dioxide ($PbO_2$). Thus the two plates are made dissimilar, since one of the lead plates has been changed at the surface into lead dioxide, a reddish-brown deposit which can be seen if we look at the anode carefully. The other plate is gray and somewhat spongy.

Next let us connect to a voltmeter the cell which we have just charged. It may show as high a difference of potential between the two plates as 2.2 volts. The lead dioxide plate becomes the positive plate. While the cell is discharging, the lead dioxide is being converted into lead sulfate, and water is being formed. When the surfaces of both plates become coated with lead sulfate so that both plates are similar, no more current can flow from the cell. Fortunately the process can be reversed by charging the cell again. The equation which represents the chemical action follows:

$$\underset{\leftarrow \text{ Discharging}}{\overset{\text{Charging } \rightarrow}{2PbSO_4+2H_2O \rightleftarrows PbO_2+Pb+2H_2SO_4}}$$

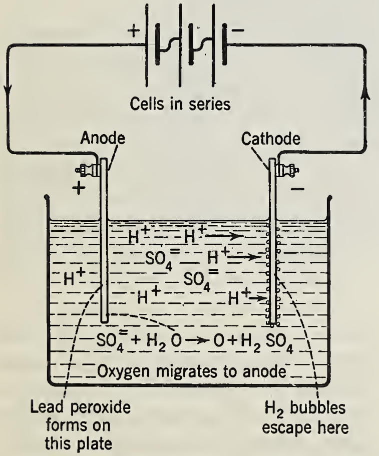


Fig. 634. The chemical action that occurs during the charging of a storage cell.

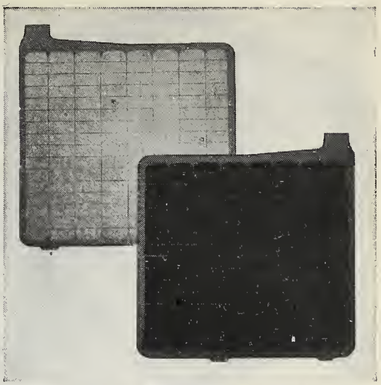
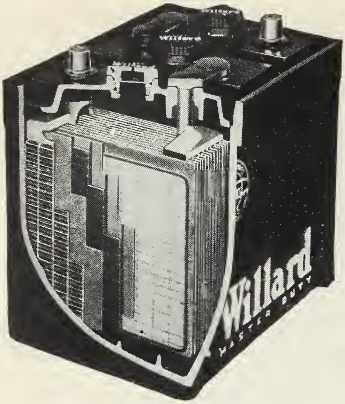

*Courtesy of the Willard Storage Battery Company*

Fig. 635. Positive and negative plates of a lead storage cell.

The specific weight of concentrated sulfuric acid is a little more than 1.800, and that of water is 1.000. Suppose that we have a cell that is fully charged. The specific weight of its electrolyte, which is a mixture of water and sulfuric acid, is 1.300. Since water is formed while a cell is being discharged (see equation) the specific weight may drop as low as 1.150. The specific weight rises again when the cell is re-charged, since water is decomposed and sulfuric acid is formed. For this reason, a hydrometer may be used to determine whether a storage battery needs re-charging.

**589. How is the commercial lead storage cell constructed?** Usually the commercial cell does not differ from the experimental cell discussed in Section 588. The chemical action is the same, but the plates are more efficient. The positive plate, Fig. 635, has a large number of grids packed with lead dioxide. This distributes the active lead dioxide through the plate as well as at its surface. The negative plate has a large number of small cells or pockets filled with spongy lead to in-

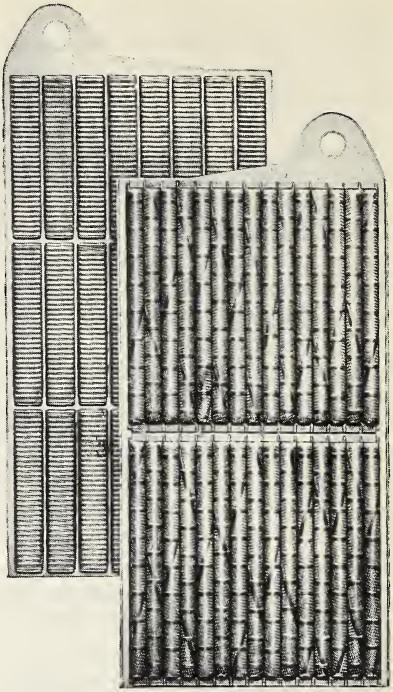


*Courtesy of the Willard Storage Battery Company*

FIG. 636. Cut-away view of a lead storage cell.

crease the amount of surface of the plate. In certain cells, red oxide of lead ($Pb_3O_4$) is packed in the grids of the positive plate, and lead monoxide, or litharge (PbO), is used in the cells of the negative plate. When such a cell is charged, the lead monoxide is reduced to spongy lead, and the red lead is oxidized to lead dioxide. Separators of rubber or wood are kept between the plates so that they may be placed very close together without touching. By the use of large plates placed close together, the internal resistance is reduced to a very low figure. (See Fig. 636.)

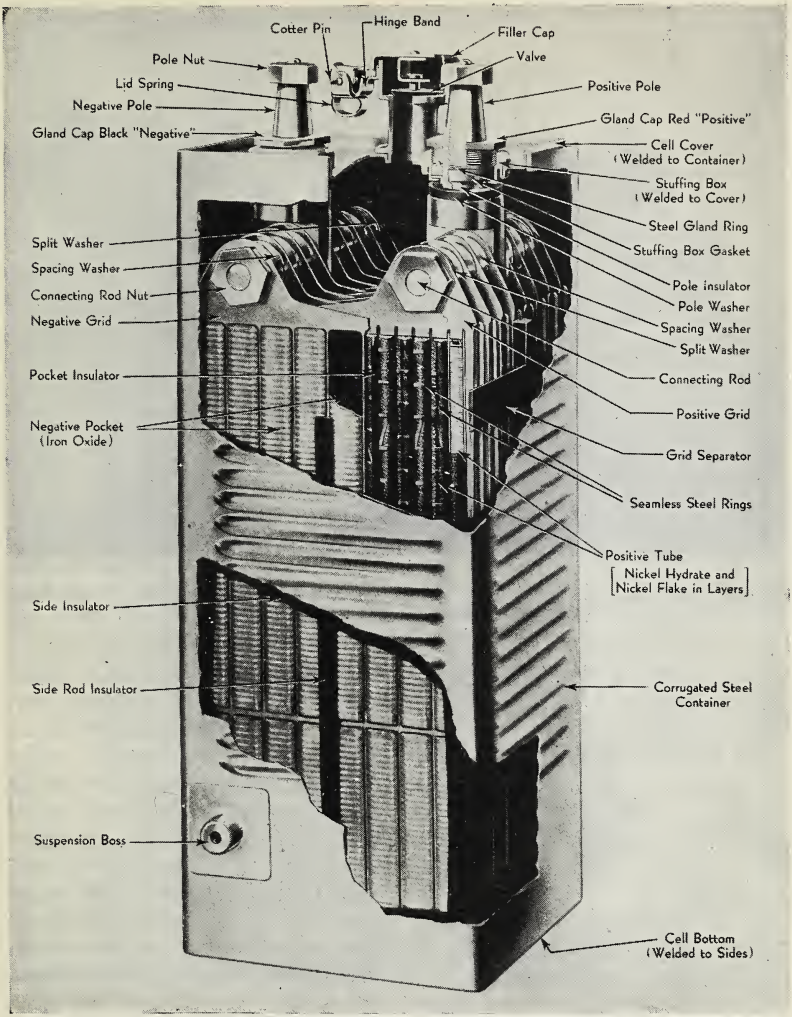
**★590. How is the Edison storage battery constructed?** Thomas Alva Edison, inventor of the incandescent lamp, the phonograph, and the motion picture machine, also devised a light, strong, durable storage battery. In this cell, the positive plate consists of nickel-plated, perforated iron tubes filled with nickel flake and hydrated nickel oxide. (See Fig. 637.) The negative plate consists of nickel-plated, perforated iron cells or pockets filled with iron oxide. The electrolyte used in this cell is caustic potash (potassium hydroxide). The elements in this cell are enclosed in a strong nickel-plated iron container. (See Fig. 638.) The chemical action is too complex to be explained here.



*Courtesy of Thomas A. Edison, Inc.*

FIG. 637. Negative and positive plates of an Edison cell.

**591. What are the advantages and disadvantages of the storage cell?** Perhaps the greatest advantage of the storage cell lies in the fact that it may be charged and discharged over and over again almost indefinitely. Since the resistance is so small, very large currents may be obtained from storage cells. In the automobile, for example, three lead cells are generally used in series. A generator, or small dynamo, is driven by the engine. When the car is running, this generator produces cur-

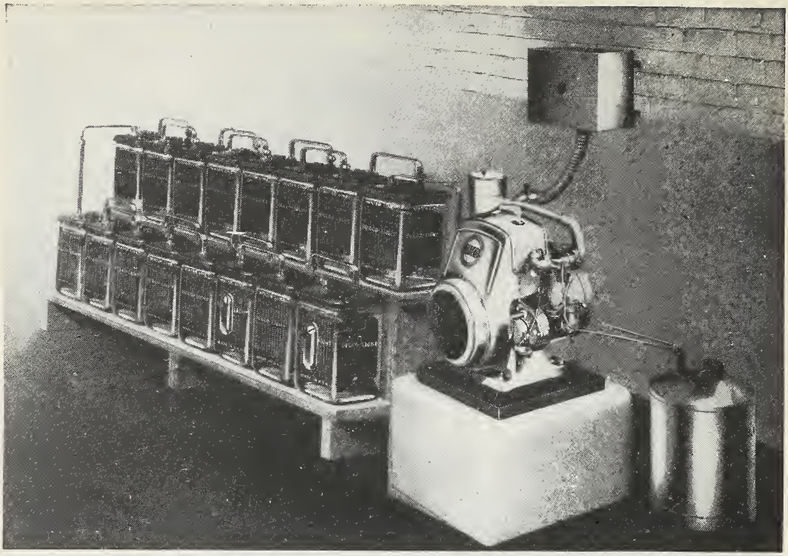

Cotter Pin
Hinge Band
Filler Cap
Valve
Pole Nut
Lid Spring
Negative Pole
Gland Cap Black "Negative"
Positive Pole
Gland Cap Red "Positive"
Cell Cover (Welded to Container)
Stuffing Box (Welded to Cover)
Steel Gland Ring
Stuffing Box Gasket
Split Washer
Spacing Washer
Connecting Rod Nut
Negative Grid
Pole insulator
Pole Washer
Spacing Washer
Split Washer
Connecting Rod
Pocket Insulator
Positive Grid
Negative Pocket (Iron Oxide)
Grid Separator
Seamless Steel Rings
Positive Tube [Nickel Hydrate and Nickel Flake in Layers]
Side Insulator
Side Rod Insulator
Corrugated Steel Container
Suspension Boss
Cell Bottom (Welded to Sides)

*Courtesy of Thomas A. Edison, Inc.*

FIG. 638. Cut-away view of an Edison storage cell.

rent to charge the storage battery. The horn, the self-starter, the lights, and the ignition system all draw current from the storage battery.

The lead storage cell is heavy, and, under the best conditions, its efficiency is not more than 75%. The lead cell must not be completely discharged. It is also injured by charging it too rapidly, or by drawing too large currents from it and discharging it too rapidly. When fully charged, it should show a voltage of about 2.2 and the specific weight of the electrolyte should



*Courtesy of the General Motors Corporation*

FIG. 639. A charging unit for a set of storage cells for use in home lighting where electric service is not available.

be about 1.300. If the voltage of the cell falls below 1.8, it should be recharged at once.

The Edison storage cell is only about half as heavy as the lead cell of equal capacity. Its efficiency is somewhat less. While the lead cell may be rather easily injured, the Edison cell is strong mechanically, and it can hardly be injured by rapid charging or discharging. When a lead cell is discharged so completely that a hydrometer shows a reading of 1.200 or less, sulfation occurs and the cell may be permanently injured. The Edison cell is not injured even if completely discharged. The maximum voltage of the Edison cell is about 1.25; hence 5 Edison cells in series furnish about the same voltage as 3 lead cells in series.

**592. What are some uses of storage cells?** In country districts where electric current is not supplied, farmers use storage cells for lighting their houses. The cells are charged by a small dynamo driven by a gasoline engine. (See Fig. 639.) Storage cells are also used for telephone work. In power stations they are used when the load is very light, or to help the dynamos when the load is heavy. Some light delivery trucks use storage batteries for motive power. The electric-clock systems in school buildings are operated by storage cells. Radio sets which operate on storage cells can still be bought for use in the country where electric current is not available. We start our automobile with current from storage cells. We use them for sounding the horn, for lighting the lamps, for operating the motor of the heater, for the car radio, and for supplying the spark to the engine cylinders.

**593. How should you care for a storage battery?** The storage cell must not be short-circuited or used with too low a resistance. Distilled water must be added at intervals to replace the water that is lost during the operation of the cell. Batteries should be tested either with a voltmeter or a hydrometer. If the charge is too low, they should be re-charged at once. If a storage battery is not to be used for a period of a few months it should be fully charged before it is laid aside. Storage cells must not be charged too rapidly, nor discharged too rapidly. A run-down cell may freeze in winter.

## 3. Heating and Lighting Effects

**594. Electric current causes heat.** Let us mount two binding posts on a small wooden block and connect them with the terminals of one or two dry cells. Before we close the switch, let us join the two binding posts with two short wires connected in series. Both wires should have the same gauge number, about No. 30. Let us use copper for one of the wires and German silver for the other one. When the circuit is closed through the switch, the German silver wire will become red hot, and it will probably melt. The copper wire will also be warmed, but it is not likely to melt. Since the same amount of current flows through both wires, we conclude that the *heating effect of an electric current is greater in the wire which has the greater resistance*, if other conditions are the same. Such a result might have been predicted, because we know that resistance or friction produces heat energy. The wires leading to our electric lamps are not warmed very much, because they are made of copper and their diameter is rather large. Hence, their resistance is very small. But the thin filament of tungsten inside the bulb gets very hot. Its resistance is more than 3 times that of a copper wire of the same diameter. The diameter of the filament is small enough so that the resistance usually varies from 20 ohms to several hundred ohms. (See Fig. 640.)

Let us repeat the experiment, first joining the two binding posts with a few inches of No. 28 copper wire. If we pass the current from a single cell through the wire, it may glow feebly. If the current from two or three cells in series is passed through the wire, it will probably melt. We find that *the heating effect increases with the number of amperes of current flowing in the circuit.*

**595. What are Joule's laws?** It was James Prescott Joule, an English physicist, who first studied the relationship between heat and work. He was also a pioneer in the mathematical study of the heating effect of the electric

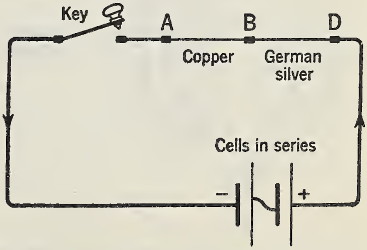


FIG. 640. Heating effect of the electric current.

current. He carried out a series of experiments and then formulated several laws that enable us to determine quantitatively the amount of heat developed in a conductor when a current is flowing through it. The following statements are known as JOULE'S LAWS:

LAW 1. *The amount of heat produced is directly proportional to the resistance of the conductor in ohms.*

LAW 2. *The amount of heat produced is directly proportional to the square of the current in amperes.* For example, 2 amperes flowing through a conductor will produce four times as much heat as a single ampere.

LAW 3. *The amount of heat produced is directly proportional to the time the current flows.*

If the amount of heat is to be expressed in *calories,* then the product of the *square of the current in amperes* ($I$) times the *resistance in ohms* ($R$) times the *number of seconds* ($t$) must be multiplied by the *constant quantity 0.24.* Expressed as a formula, we have:

$$\text{Calories} = I^2R \times t \times 0.24.$$

PROBLEM. The heating coil in a coffee percolator has a resistance of 22 ohms and uses 5 amperes of current. How long will it take to heat one liter of water from 20° C. to the boiling point, 100° C., in such a percolator?

*Solution.* To heat one liter of water (1000 gm.) from 20° C. to 100° C. requires 80,000 calories. Substituting the values in the formula,

$$\text{calories} = I^2R \times t \times 0.24,$$

we have

$$80{,}000 = 5 \times 5 \times 22 \times t \times 0.24;$$

whence $t$ equals 606 seconds, just a trifle more than ten minutes.

**596. How do we use electric heat?** We are all familiar with the electric *curling iron,* the electric *hair drier,* the electric *flatiron,* the electric *bread-toaster,* the electric *waffle-iron,* the electric *coffee percolator,* the electric *grill,* and the electric *heater.* (See Fig. 641.) In some cases, the electric *heating pad* takes the place of the hot-water bottle in the sick room. A wire heated electrically is used to cauterize wounds or to burn away growths of surplus tissue. Trolley cars are usually heated by electric heaters. In the majority of these electrical heating appliances, coils of high resistance wire, usually made of *nichrome,* are so grouped that a great deal of heat is concentrated in one place. (See Fig. 642.) At the prices charged for electrical energy in many localities, it costs more to heat or cook by electricity than it does by the use of gas or some other fuel. Power companies in some localities are beginning to make lower rates to small consumers

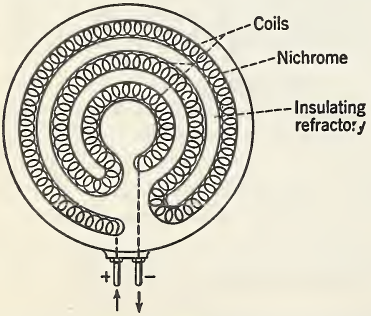


FIG. 641. Electric heater, with its coils of nichrome wire.

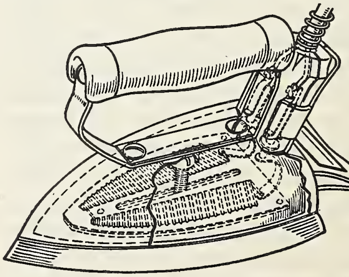


FIG. 642. Cut-away view of an electric flatiron, with heating coils exposed.

who use electricity for refrigeration, for operating washing machines, and for cooking.

If two pieces of wire are placed end to end and a current is passed through them, the heat developed at the point of contact is sufficient to *weld* them into one piece. You have probably observed trolley companies using electric welding on their tracks. Current for such purpose is drawn from the trolley wire. At one time, metal plates used for construction work were riveted together. Now the edges of such metal plates are usually welded together by means of the electric current. (See Fig. 643.)

Courtesy of Westinghouse

FIG. 643. Electric welding is gradually displacing the riveting machine. Metals are being welded together.

**597. How may wires be overloaded?** We found from experiment that the current from a couple of dry cells joined in series is sufficient to melt a short piece of No. 30 copper wire. If we send the same amount of current through a short piece of wire of the diameter used for wiring dwellings (No. 14), the wire will be heated, but it is not likely to melt. The larger wire has the greater *carrying capacity*. By the capacity of a wire we mean the *number of amperes which it can carry safely*. A bare wire has a greater carrying capacity than an insulated wire of the same diameter. A wire outside, where the air circulates freely, has a greater carrying capacity than the same wire inside the walls of a building. If we try to force more current through a wire than it can carry *safely*, we have an *overload*. Such a wire may melt, and it may set fire to any flammable material that is near it.

There are two common ways in which a person may cause an overload in the wiring circuit in his home.

1. *By putting too many appliances on one circuit.* Suppose that your electric wires can carry 17 amperes safely. You have two sandwich toasters and a coffee percolator plugged in, and each one takes about 5 amperes of current. It may be chilly in the room and some one turns on an electric heater, which uses at least 5 amperes more of current. You now have appliances enough to take 20 amperes of current from a line which can carry safely only 17 amperes. Such an overload may blow your fuses or melt the wires.

2. *By a short circuit.* You have a floor lamp and the duplex cord is old, worn, and possibly kinked. Possibly the insulation is worn away at places. If someone steps on the cord, he may press the two wires together so that they touch and form a short circuit. To show why a short circuit causes an overload, let us suppose that we have a lamp which has a resistance of 500

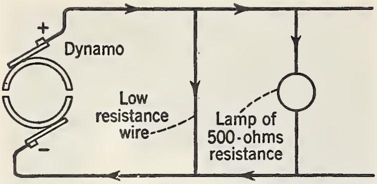


FIG. 644. The greater part of the current flows through the low-resistance wire.

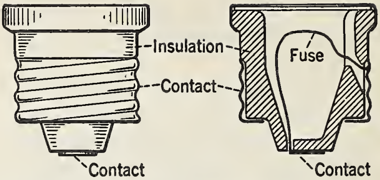


FIG. 646. Plug-type fuses. The fusible metal is surrounded by non-flammable material.

ohms operating on a 110-volt circuit. The current which flows through the lamp is 0.22 ampere (Ohm's law). If we scrape the insulation from the wires and join them by a heavy piece of low resistance wire, we have a short circuit. (See Fig. 644.) To make the calculations simple, let us assume that the wire used has a resistance of exactly one ohm. The current would immediately rise to 110 amperes. Let us compare the heating effects in the second case with those of the first.

$$\frac{I^2R}{I^2R}, \text{ or } \frac{110 \times 110 \times 1}{0.22 \times 0.22 \times 500} = 500.$$

Hence, in this example the amount of heat produced when the wires are short-circuited is 500 times as much as before. Naturally the wires would melt. Such a short circuit might be produced by the wires being brought into accidental contact during a fire or a storm.

**598. How are fuses a protection?** We know that an overload may cause a fire. Even if the wires did not set fire to our house, they might melt *at any place* within the walls or ceiling. It would be troublesome to locate the break in the circuit and expensive to make repairs. To prevent such an occurrence, *fuse wires* are used in all wiring circuits. In dwelling houses, the fuses are placed in metal boxes, usually installed in the basement. (See Fig. 645.) The fuse plugs of Fig. 646 are in common use. The contact points are shown in the sectional view. The fusible wire is surrounded by insulating material. When an overload occurs, the fuse wire melts and breaks the circuit. It is a simple matter to replace the fuse after the cause of the overload has been removed. Sometimes a cartridge fuse is used in certain circuits. (See Fig. 647.)

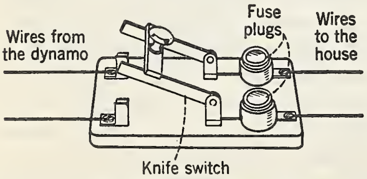


FIG. 645. Fuses and a knife switch are used for protection.

When an electrician wires a house, he plans for a certain number of lights and appliances for each circuit. Then he installs a fuse which has *lower* carrying capacity than that of the wires themselves. Suppose that the wires have a carrying capacity of 17 amperes. Then a 10- or 15-ampere fuse installed in the circuit will melt more readily than the wire itself. A 25-ampere fuse plug is poor protection for such wires.

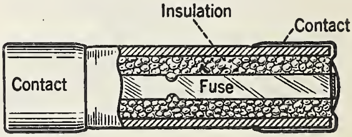
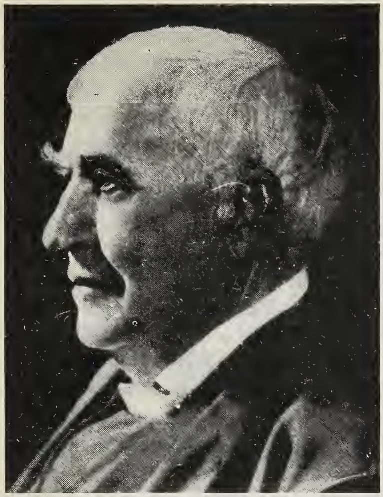


FIG. 647. A cartridge fuse, showing fusible metal.



*Courtesy of Thomas A. Edison, Inc.*

FIG. 648. Thomas Alva Edison (1847–1931) was one of our most prolific American inventors. He is best known for his invention of the incandescent lamp in 1879. He is also the inventor of the phonograph, the motion-picture machine, and the Edison storage cell. He contributed, too, to the development of many other appliances. Edison was a tireless worker, often toiling far into the night.

FIG. 649. This shaft at Menlo Park was built as a memorial to Thomas A. Edison for his invention of the incandescent lamp.

**599. Edison made the first incandescent lamp.** About three score years ago, Thomas Edison conceived his idea of what came to be known as the "light in a bottle." (See Fig. 648.) Edison exhibited his incandescent lamp in 1879 in his laboratory at Menlo Park, New Jersey. (See Fig. 649.) Edison tried almost every kind of fiber in his effort to find a filament for his lamp, even using a hair from the beard of one of his assistants in one experiment. The filament had to have a high electrical resistance; it could not be too brittle; its melting point had to be very high; it had to be enclosed in a vacuum bulb so that it would not burn or unite with the oxygen from the air. After a search of a couple of years, he finally was successful in the use of a filament of carbon made by heating bamboo fiber. (See Fig. 650.)

But the finding of a filament which was satisfactory did not solve the entire problem. The ends of the filament had to be connected to two short pieces of wire that could be sealed in glass.

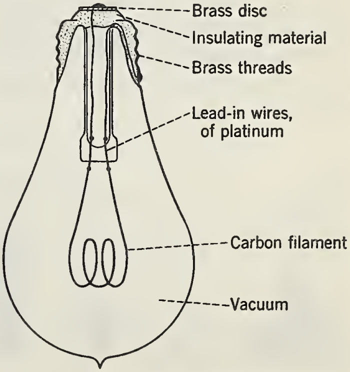
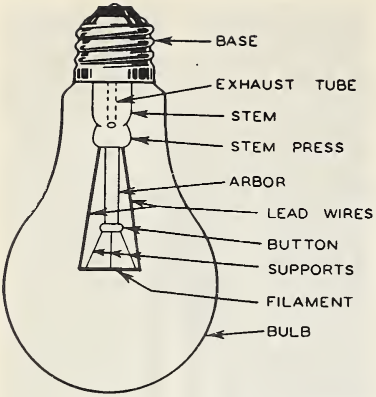


FIG. 650. A diagram of the old carbon lamp invented by Edison.



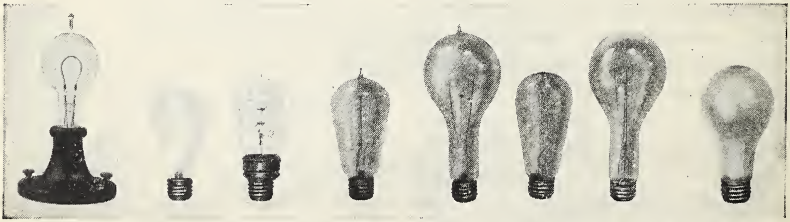
*Courtesy of Westinghouse*

Fig. 651. Diagram of a tungsten lamp.

If the metal expanded more than the glass upon heating, it would contract more upon cooling and the seal would not be perfect. Platinum was found to have the same coefficient of expansion as glass. Hence, two pieces of platinum wire were used in the early carbon lamps. The other ends of the platinum wires were connected by copper wires, one to a brass disc, and the other to a threaded cylinder. Both the disc and cylinder make connections with the terminals of the lighting circuit when the bulb is screwed into the socket. These incandescent lamps were first used for lighting at Roselle Park, New Jersey, and soon began to be used extensively.

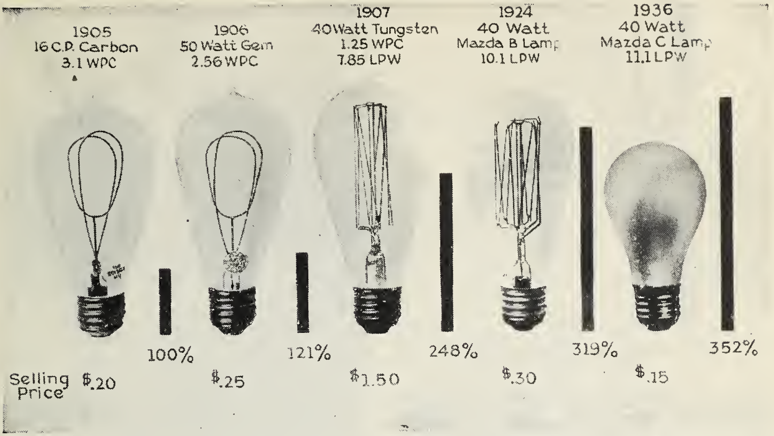
**600. Tungsten lamps are better lamps.** Men of science are never satisfied. Extensive search for a better filament than one made of carbon was made. The carbon filament was metalized. Tantalum was tried with some success. But the most satisfactory metal used thus far for the filament is *tungsten.* Engineers learned how to draw tungsten wire, a difficult feat. Tungsten has the following desirable properties: (*a*) It has an exceedingly high melting point; (*b*) it has a high resistance; (*c*) it is not too brittle; (*d*) it evaporates slowly, even at a high temperature. The filament in the modern tungsten lamp is not coiled, but it is bent back and forth over the ends of bent wire supports known as anchors. (See Fig. 651.) In the present lamp, the bulb is frosted on the inside to prevent the glare from the hot filament. An alloy consisting largely of nickel and iron has been made which takes the place of the expensive metal platinum for use as "lead-in" wires. (See Fig. 310.)

The tungsten lamp has made the carbon lamp practically obsolete. It gives a whiter light than the yellowish light of the carbon lamp and its efficiency is from 2.5 to more than 3 times as great. We now pay about the same price for operating a 50-C.P. lamp that our parents used to pay for operating



*Courtesy of the General Electric Company*

Fig. 652. The development of the incandescent lamp.


1905
16 C.P. Carbon
3.1 WPC
1906
50 Watt Gem
2.56 WPC
1907
40 Watt Tungsten
1.25 WPC
7.85 LPW
1924
40 Watt
Mazda B Lamp
10.1 LPW
1936
40 Watt
Mazda C Lamp
11.1 LPW
100%
121%
248%
319%
352%
Selling Price
$.20
$.25
$1.50
$.30
$.15

*Courtesy of the General Electric Company*

FIG. 653. The newest of the lamps have a coiled coil of wire as a filament.

a 16-C.P. lamp. Some engineers estimate that the introduction of the tungsten lamp has meant a saving of at least $1,000,000,000 annually to the people of the United States. (See Fig. 652.)

The gas-filled tungsten lamp has largely taken the place of the vacuum tungsten lamp. The bulb is first evacuated and then filled with a mixture of nitrogen and argon. The filament is wound in a close spiral to prevent the loss of heat by radiation. In some cases, a *coiled coil* is used as the filament. The efficiency is increased by the use of the nitrogen-argon mixture because the filament can be heated to a higher temperature. The gas molecules get in the way and tend to prevent the evaporation of the hot filament and the consequent darkening of the bulb. Argon is peculiar since it gets a job simply because it is inactive and succeeds in getting in the way. (See Fig. 653.)

The large-sized gas-filled lamps may need only 0.6 watt per candle power of light. The smaller ones take about 1 watt per candle power. Incandescent lamps are usually grouped in parallel. The voltage between the terminals is constant. (See Fig. 654.) Each lamp is thus independent of all the others. If each lamp takes one ampere of current, then each lamp that is turned on increases the amount of current flowing in the main circuit by one ampere.

**601. How does the arc lamp work?** When two carbon rods, which are connected to the terminals of an electric generator, are brought together momentarily, the heat produced at the point of contact is great enough to vaporize some of the carbon and produce an intensely bright light. If the carbon rods are separated about a quarter of an inch, the circuit is not broken because the carbon vapor con-

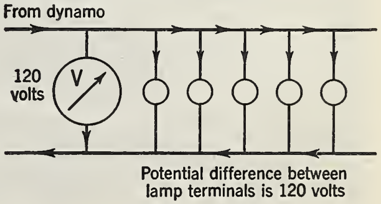

From dynamo
120 volts
V
Potential difference between lamp terminals is 120 volts

FIG. 654. Incandescent lamps are wired in parallel.

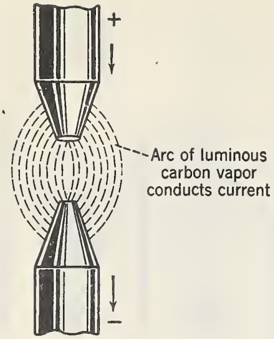


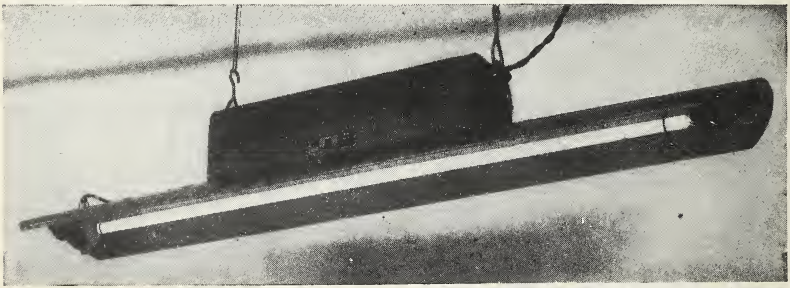
Fig. 655. A carbon arc lamp.

tinues to conduct the current from one rod to the other. (See Fig. 655.) The light comes from the extremely hot, luminous carbon vapor which forms the arc. A clutch mechanism is used to gradually lower the upper carbon rod and regulate the distance between the two carbon rods. The clutch mechanism is controlled by means of an electromagnet.

Arc lights are usually operated on a line where the difference of potential between the carbon rods is about 50 volts. They use from 10 to 25 amperes of current. Because the arc lamp is efficient, it was at one time extensively used for street lighting. Such use is now nearly obsolete, but the arc lamp finds use in commercial motion-picture machines, and in spotlights and searchlights.

**602. How are vapor lamps constructed?** One type of *mercury vapor lamp* is extensively used in drafting rooms and by photographers. The electrodes are sealed in the ends of a glass tube which may be 3 or 4 ft. in length. The lamp is so suspended that the tube is slightly inclined, and the lower end contains metallic mercury. (See Fig. 656.) If the tube is tipped so that a thin column of mercury makes contact momentarily between the electrodes, an arc is established. The heat causes the mercury to vaporize, and the whole tube becomes filled with the luminous mercury vapor. This lamp is efficient, but it is deficient in red rays. Neon tubes are sometimes used with mercury vapor lamps to supply the orange and red rays.

The mercury vapor lamp is rich in ultra-violet rays. Such rays do not pass through glass readily, but they do pass through quartz. Mercury vapor lamps made out of quartz are useful for sterilizers, since ultra-violet rays destroy bacteria. (See Fig. 657.) Some of the sun lamps used by physicians are of this type. The lamp of Fig. 658 is made of a special glass which transmits ultra-violet light. The tungsten coil



*Courtesy of General Electric Vapor Company*

Fig. 656. The mercury vapor lamp is rich in ultra-violet rays.

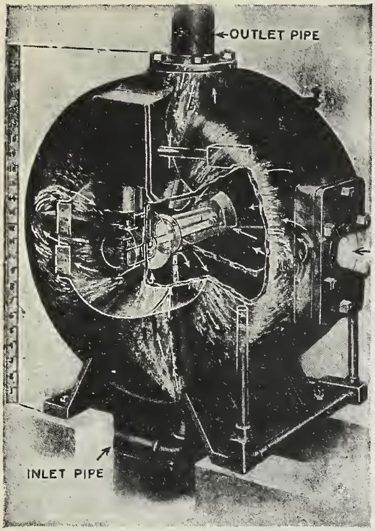


Fig. 657. Phantom view of a water sterilizer.

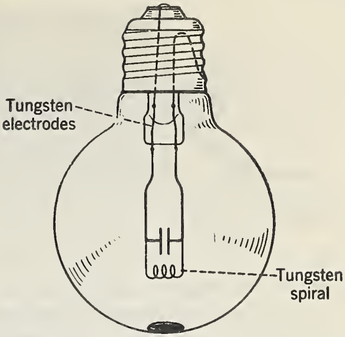


Fig. 658. A lamp designed to produce ultraviolet rays.

heats and vaporizes the mercury. The mercury vapor then forms an arc between the tungsten electrodes.

Smaller-sized mercury vapor lamps have been developed and used to some extent for road illumination. Another type of vapor lamp uses the vapor from sodium, a light metal. It is coming into use rather rapidly for road illumination. A road lighted with *sodium vapor* lamps as shown in Fig. 659 makes the use of bright headlights unnecessary.

**603. Neon lamps are economical.** The use of neon lamps has been mentioned. Everywhere we see them being used for advertising purposes. The gaseous neon is found in the atmos-

Fig. 659. Vapor lamps are coming into use for road illumination.

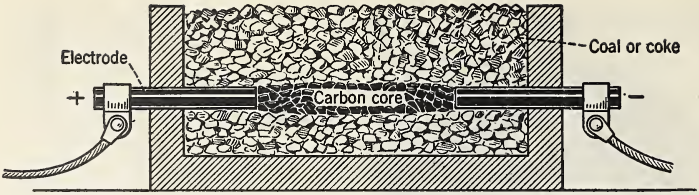


FIG. 660. The carbon core offers resistance in this furnace used for making graphite. Furnaces of this type are also used for making calcium carbide and silicon carbide.

phere in exceedingly small quantities. It is one of the by-products obtained from liquid air. The glass tube, which may be of any shape or design, is evacuated. Then neon is admitted until the pressure of its vapor amounts to about 10 mm. of mercury. The current is supplied to electrodes sealed in the ends of the tube.

The cost of operating neon tubes is ridiculously small, because the current consumption amounts to only a few thousandths of an ampere. In fact, the cost is so small that some advertisers hardly trouble to turn off the current even in the daytime. The effect is particularly striking because the entire tube is filled with the *luminous gas.* Different colors may be obtained by the use of small quantities of other gases, or by the use of colored glass.

**604. Electric furnaces give high temperatures.** Two types of electric furnace are in use.

1. *Resistance furnaces.* In furnaces of this type, an electric current is passed through a coil of wire made of platinum, nichrome, tungsten, or molybdenum which is wound upon some refractory material. The substance to be heated is placed inside the coil. Possibly your dentist uses such a furnace in the making of artificial teeth. In such a resistance furnace a temperature of from 1000° C. to nearly 2000° C. can be obtained.

In another type of resistance furnace, the heat is produced by the resistance which the material in the furnace itself offers to the passage of the current between the electrodes, which are placed at the opposite ends of the furnace. Furnaces used for making calcium carbide, silicon carbide, and artificial graphite are of this type. (See Fig. 660.)

2. *Arc type furnaces.* Exceedingly high temperatures are obtained in the arc type furnaces. The temperature is estimated at about 3500° C. The electric arc is formed between two carbon rods in a refractory crucible in which the contents to be heated are placed. (See Fig. 661.) At one time, heat from an arc type of furnace was used to make nitrogen compounds from the free nitrogen present in the air. An electric furnace used for making steel is a kind of combination arc and resistance type.

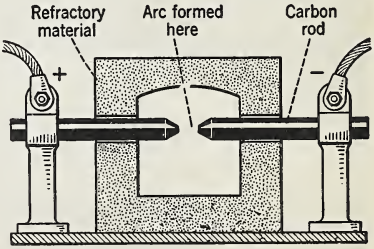


FIG. 661. The arc type of electric furnace. The temperature produced may reach 3500° C.

## Summary

An electric current produces a magnetic effect. If we grasp the conductor so that the extended right thumb points in the direction of the current flow, the fingers encircle the wire in the direction of the lines of force.

An electro-magnet consists of a soft iron core wound with a number of turns of insulated wire. The strength of the electro-magnet depends upon the number of ampere turns.

Electrolysis is the decomposition of a compound by means of an electric current. The current enters an electrolytic cell by the anode and leaves by the cathode. Hydrogen and most metals are electro-positive; they are attracted to the cathode. The non-metals, which are electro-negative, are attracted to the anode.

The ordinary storage cell consists of two lead plates immersed in a solution of sulfuric acid. They become dissimilar when an electric current is passed through the cell; two dissimilar plates immersed in an electrolyte produce a difference of potential. No electricity is stored in a storage cell.

An electric current produces a heating effect. The amount of heat produced is proportional to the time, the resistance, and the square of the current strength. Electric lighting is merely a modified application of the heating effect of the electric current.

*How many of the following terms can you define or explain?* (*You may call the chapter "Electricity As It Is Related to Yourself."*)

Oersted's discovery
Right-hand rule
Electro-magnet
Operation of electric bell
Key
Teletype
Morse
Electrolytic cell
Electroplating
Charles M. Hall
Sir Humphry Davy
Heating by electricity
Overload
Fuse wires
Tungsten lamp
Vapor lamps
Direction of current flow
Polarity of solenoid
Ampere turns
Telegraph
Sounder
Relay
Morse code
Electrolysis of water
Electrotyping
Michael Faraday
Storage cell
Joule's laws
Short circuit
Incandescent lamp
Neon lamps
Electric furnace
Edison cell

## QUESTIONS

1. If a helix is supported so that it is free to rotate, what position does it assume when a current is passed through it?

2. How could you tell in what direction a current is flowing through a wire in the ceiling of a room? If the ends of the wires are exposed, how can you tell which is the positive terminal by dipping the wires into solution of copper sulfate?

3. Why is an iron core used in an electro-magnet? Would steel do as well? Give two reasons for your answer.

4. What is triple-plated silverware? What does the mark "12 Dwt." mean as used so frequently on silver-plated ware?

5. Draw a diagram to show an apparatus that might be used for plating an object with gold. Label your diagram carefully.

6. In what two ways can one find the polarity of an electro-magnet?

7. What is actually stored in a storage battery?

8. What is meant by the "carrying ca-

pacity" of a conductor? What does the expression "overload" mean?

9. How can Faraday's second law be used in determining the strength of an electric current?

10. What is meant by a "short circuit"? In what way is a "short circuit" dangerous? How are fuses used to eliminate such a danger?

11. Would you use a 25-ampere fuse plug with a wire which can carry safely only 17 amperes? Explain fully.

12. In what two ways may the wiring of a flatiron be varied to concentrate the heat at the point? What is the advantage of a "hot-point" flatiron?

13. How much is the heat in a circuit increased if the resistance is doubled and the amount of current unchanged? How much is the heat increased if the current is doubled and the resistance unchanged?

14. Explain why the wires leading to an electric bulb do not become so highly heated as the filament itself, since the same amount of current may flow in each.

15. Make a list of the things to be done in taking care of a storage battery.

16. Why must an electro-plater be familiar with Faraday's laws of electrolysis?

17. A storage cell charged to its maximum capacity has a pressure of 2.2 volts. Can a single dry cell, E.M.F. equals 1.5 volts, be used to charge this cell? Can it be charged by two such cells in series? How many cells in parallel grouping would be required?

## PROBLEMS

### Group A

1. How much silver will a current of one ampere deposit in 15 min.? How much copper will the same current deposit in the same time?

2. If the resistance of a lamp is 220 ohms and the current flowing through the lamp is 0.5 ampere, how many calories of heat will be produced in an interval of 10 minutes?

3. A lamp operates on a 110-volt circuit. Its resistance is 550 ohms. How many calories of heat will be developed in 30 minutes? How many grams of water at 20° C. could be warmed to 80° C. by the heat that is set free by the lamp?

2

### Group B

4. A coil of wire has a resistance of 22 ohms. If it is connected with a 110-volt circuit, how many grams of ice could be melted by the heat which the coil would set free in 10 minutes?

5. A 3-kgm. flatiron uses 5 amperes of current when operating on a 120-volt circuit. How long will it take to heat the flatiron from 20° C. to 200° C., if there is no loss of heat by radiation? (Sp. ht. of iron is 0.113.)

6. A coffee percolator has a heating coil of 20 ohms resistance. How many calories of heat does it liberate per second when it operates on a 100-volt circuit? How is the amount of heat liberated per second affected if it is connected to a 120-volt circuit? If used on a 110-volt circuit?

# *Measuring Instruments*

## 1. Instruments Used for Measurement

**605. Introduction.** We have had some important electrical units defined, and electrical measuring instruments have been mentioned several times. To find difference of potential in volts, one uses a *voltmeter*. We use an *ammeter* to measure the strength of the current in amperes. A *resistance box* or a set of *resistance coils* may be used to measure electrical resistance in ohms. To measure consumption of electrical energy, a *watt-hour meter* is used.

**606. What is a galvanoscope?** We have learned that a current flowing through a wire sets up a magnetic field around the wire. Let us wind the wire into a loop and place a compass needle in the center of the loop. When a current flows through the loop, the needle is deflected. (See Fig. 662.) Just as one might suspect, increasing the number of turns in the loop increases the deflection. By the use of a large number of turns, even a feeble current will cause a marked deflection of the needle.

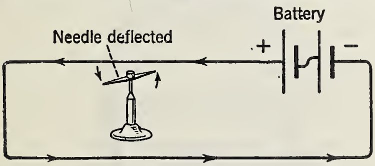


Fig. 662. A current flowing through a loop of wire affects the magnetic needle.

A device similar to the one shown in Fig. 663 may be used to show how increasing the number of turns in the coil increases the deflection of the needle. It is called a *galvanoscope. It may be used to detect the presence of an electric current* or to *determine its direction.*

**607. What is the purpose of the galvanometer?** Sometimes it is necessary to do more than to detect the presence

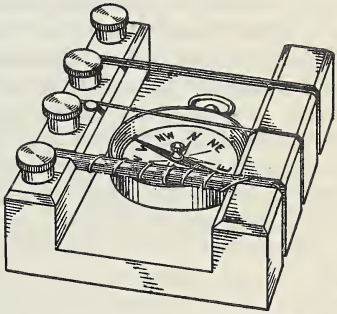


Fig. 663. A simple galvanoscope.

### Vocabulary

Kilowatt-hour, 1000 volt-amperes for one hour. The unit used for measuring electrical energy.

Galvanometer, an instrument for detecting the presence of an electrical current or for measuring its strength.

Rheostat, high-resistance coils used for introducing resistance into a circuit or for measuring resistance.

Shunt, either branch of a divided circuit.

Galvanoscope, an instrument for detecting the presence of an electric current.

Refractory, not easily melted.

Watt-hour, one volt-ampere for one hour.

of a current or to determine its direction. Often we need to measure its strength or to find the voltage. It is possible to have a *galvanometer of the movable needle type* which can be so calibrated that it can be used as a measuring instrument.

The *movable-coil galvanometer* is much more common. A coil of wire is pivoted between the poles of a permanent horseshoe magnet. It is really a helix which becomes magnetized when current flows through it. Hence we have two magnets: (*a*) A permanent horseshoe magnet which is firmly mounted on the base of the instrument; (*b*) an electro-magnetic helix, which is free to turn upon its axis. When current flows through the helix, its faces acquire polarity, and they are attracted and repelled by the poles of the permanent magnet. A small light pointer, attached to the coil, moves along a graduated scale whenever the coil turns on its axis. Increasing the strength of the current flowing through the coil or helix increases the strength of its magnetism, and consequently the amount of its deflection. A small coiled spring holds the coil at such a position that the pointer shows a zero reading when no current is flowing through it. (See Fig. 664.) Some galvanometers have a small mirror attached to the coil. A beam of light reflected from this mirror to a scale several feet in length enables one to detect the slightest movement of the galvanometer coil. The beam of light thus becomes a pointer several feet in length that serves to magnify the amount of deflection.

**608. How does the voltmeter work?** Many *voltmeters* are really galvanometers of the movable-coil type. They are so graduated that they read potential difference directly in volts. The movable coil consists of fine insulated wire wound on a light frame called a *former*. The coil is pivoted on jeweled bearings to reduce friction to a minimum and mounted between the poles of a permanent magnet of high retentivity. The current enters through two springs which hold the coil in such a position that the pointer stands at the zero mark of the graduated scale when no current is flowing.

Since a voltmeter really measures the *difference of potential* between two points in an electrical circuit, a coil of *high resistance* must be connected in series with the movable coil. Then just enough current will flow through the coil to magnetize it slightly and cause a deflection of the needle, but there will not be enough current flowing to *lower* the difference of potential while readings are being taken. Two or more resistance coils may be used in the same instrument to enable the user to measure different voltage ranges by the use of different binding posts which make connections with the source of current. *All voltmeters are high-resist-*

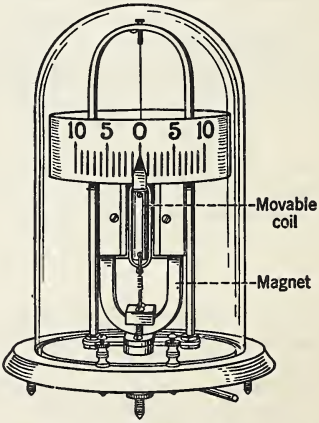
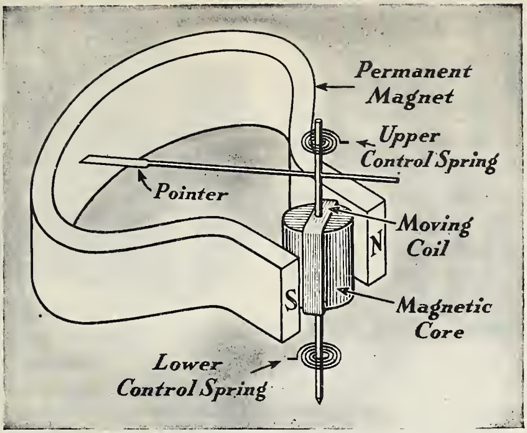


Fig. 664. A galvanometer of the movable-coil type.


Permanent Magnet
Upper Control Spring
Pointer
Moving Coil
N
S
Magnetic Core
Lower Control Spring

*Courtesy of the General Electric Company*

FIG. 665. Magnet and coil of voltmeter.

*ance instruments.* They are connected in *parallel* across a circuit to any two points between which one wishes to find the difference of potential. (See Fig. 665.)

**609. How is the ammeter used?** In construction, the ammeter does not really differ from the voltmeter. It is a *low-resistance* instrument. Since it is used to measure the amount of current flowing in a circuit, it must be connected in *series* in that circuit. If it offered more than a minute amount of resistance, it would reduce the amount of current flowing in the circuit because of its own resistance. The coil may be wound with a few turns of coarse, low-resistance wire. More often, the winding is the same as that used for the voltmeter, but instead of having a coil of high resistance in series with it, a *low-resistance shunt* is connected across its terminals. In that way, the resistance of the ammeter becomes negligible, since nearly all the current flows through the shunt.

The diagram, Fig. 666, shows how the same instrument may be used either as a voltmeter or an ammeter. In either case, the plus terminal of the circuit is always connected to the binding post marked "volts" or "amperes." To use it as an ammeter, we connect the negative terminal to the binding post marked "15 amps." Then any amperage from 0 to 15 can be read with the

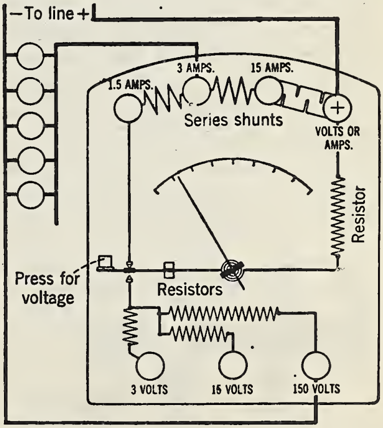

—To line +
1.5 AMPS.
3 AMPS.
15 AMPS.
+
Series shunts
VOLTS OR AMPS.
Resistor
Press for voltage
Resistors
3 VOLTS
15 VOLTS
150 VOLTS

FIG. 666. Wiring scheme of a variable-range voltmeter and ammeter.

instrument. When the negative terminal is connected to the post marked "3 amps," as shown in the diagram, then the range is from 0 to 3 amperes. This makes a more sensitive instrument, because the needle swings five times as far with one ampere of current as it would with the first connection. It may be made 10 times as sensitive by connecting the negative terminal to the binding post marked "1.5 amps."

When the negative terminal is connected to the binding post marked "150 volts," the instrument may be used for any voltage from 0 to 150. The sensitivity may be increased by making the connection with the post marked "15 volts," when the range will be from 0 to 15 volts. The sensitivity is increased still more by joining the negative terminal to the binding post marked "3 volts," when the instrument has a range of from 0 to 3 volts.

**610. How are resistance coils used?** Resistance boxes are sometimes used to measure resistance. In some cases they are used to reduce the voltage in a circuit or to decrease the amperage. They consist of coils of high-resistance wire, and they are usually made from some alloy which does not change its resistance a great deal when the temperature changes. The construction is such that it is possible to connect one or more of the coils in series and thus vary the total resistance as desired. In Fig. 667, for example, the current will flow through the brass strips, *BB′*, when the brass plug, *P*, is inserted, instead of flowing through the coil *C*. The current flows through the coil *C′* and it can be made to flow through coil *C* by removing the plug. Each coil has a different resistance, and a wide variation is possible by removing different plugs or different combinations of plugs. (See Fig. 668.)

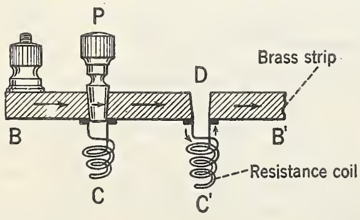
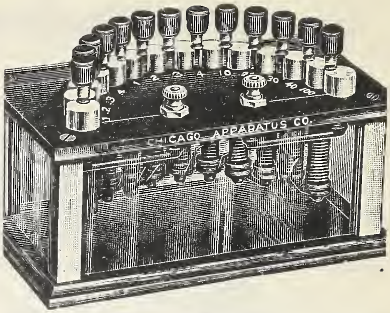


Fig. 667. Resistance coil, showing winding.



*Courtesy of the Chicago Apparatus Company*

Fig. 668. Resistance coils for measuring resistances.

**611. What is a rheostat?** This name is given to any device that is used to vary the flow of current by means of variable resistances. A common form consists of a coil of wire wound on some refractory material. One end of the coil is attached to one terminal of the circuit, and the other terminal is connected to a sliding contact. As the contact is moved across the coils, as many coils may be thrown into the circuit as are desired. If we watch the motorman starting a trolley car, we see that he gradually cuts out one resistance coil after another as the car comes up to speed. Resistance coils are sometimes called rheostats, although the latter name is more often reserved for appliances used to reduce the current strength.

## 2. Series and Parallel Wiring

**612. How great is the fall of potential along a conductor?** If we have two water tanks, *C* and *D*, connected with one another as shown in Fig. 669, the difference of pressure between the two tanks is represented by a water head of 45 feet. At the point *A* in the connecting pipe the pressure has fallen until it is represented by a water head of 30 ft. The difference of pressure between the point *B* and the surface of the water in the tank *D* is represented by a water head of 15 ft. There is a continuous fall of pressure along the connecting pipe. This fall of pressure is directly proportional to the length of the pipe.

In an analogous manner, there is a fall of potential along a conductor when an electric current is flowing through it. Suppose that we have a voltaic cell whose terminals *A* and *D* are joined by a uniform wire 12 ft. long, as represented in Fig. 670. Let us use a voltmeter to test the differences in pressure between various points in the wire. The wires used for connecting electrical instruments are large enough so that their resistance is negligible. If we connect the voltmeter directly across the two terminals of the cell, we find that the difference of potential between the positive and negative plates is 2 volts. That is the *effective pressure* of the cell. If the positive plate has a pressure 2 volts higher than the negative, then we must conclude that there is *a drop of potential* of 2 volts along the 12 ft. of wire.

With one terminal of the voltmeter still connected to plate *A*, let us touch the other terminal of the wire at point *B*, which is 6 ft. from *A*. We find that the difference in pressure is just one volt. If we connect the plus terminal of the voltmeter to the wire at *B* and the negative terminal at *C*, just 3 ft. distant, the voltmeter shows a reading of 0.5 volt. Hence we conclude that the *fall of potential along a wire of uniform resistance is directly proportional to the length of the wire.*

If the external resistance is not uniform, the fall of potential occurs, but it is not gradual. Suppose that the dynamo of Fig. 671 maintains a constant P.D. of 50 volts between *A* and *C; AB*

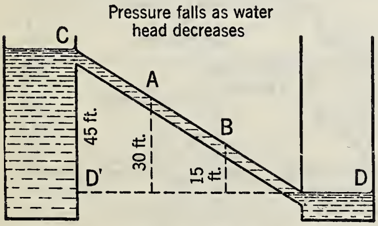


Fig. 669. The fall in pressure is directly proportional to the length of the pipe.

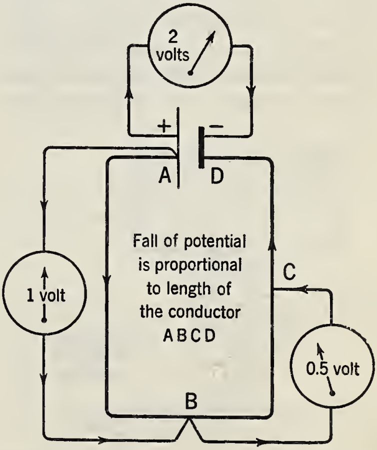

2 volts
+
−
A
D
1 volt
Fall of potential is proportional to length of the conductor ABCD
C
0.5 volt
B

Fig. 670. Fall of potential in a wire of uniform resistance.

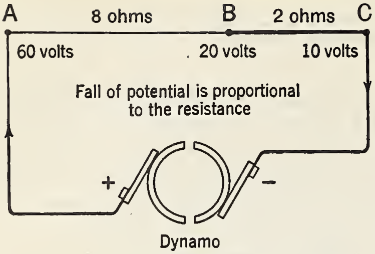

A
8 ohms
B
2 ohms
C
60 volts
20 volts
10 volts
Fall of potential is proportional to the resistance
+
−
Dynamo

FIG. 671. Fall of potential when resistance is variable.

has a resistance of 8 ohms, and the resistance of $BC$ is 2 ohms. The total resistance is 10 ohms; therefore a current of 5 amperes flows through the circuit. In order that 5 amperes may flow through $AB$, 8 ohms resistance, the P.D. between these points must be 40 volts. The P.D. between $B$ and $C$ must be 10 volts to send 5 amperes of current through 2 ohms resistance. From a consideration of these cases, it is evident that *the fall of potential is directly proportional to the resistance.*

There is a drop of potential of 40 volts through the 8-ohm resistance and a drop of potential of 10 volts through the 2-ohm resistance. 40 : 8 = 10 : 2. The student must remember that the current flowing in all parts of a series circuit is uniform. In the example just given, both the 8-ohm and the 2-ohm wires carry the same amount of current, 5 amperes. The water analogy helps to make this statement clear. (See Fig. 672.) It seems obvious that no more water can flow through the large pipes $B$ and $C$ than through the small pipe $A$. By analogy, we are led to conclude that no more current can flow through the small resistance of 2 ohms from $B$ to $C$ than that supplied to $B$ from the 8-ohm wire $AB$.

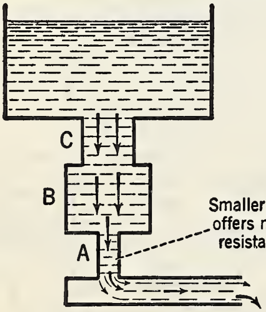

C
B
A
Smaller pipe offers more resistance

FIG. 672. The same amount of water flows through the large pipe as through the small one.

**613. What are the results of series wiring?** In a series circuit all the current flows through each appliance in turn. Suppose that we have eight lamps, $L$, all connected in series with a 112-volt dynamo as shown in Fig. 673. If each lamp has the same resistance, 100 ohms, then the total resistance of the external circuit is 800 ohms, *the sum of all the separate resistances.* The amount of current flowing through the circuit is equal to 112 ÷ 800, or 0.14 ampere. Each lamp receives the same amount of current. A voltmeter connected across the terminals of each lamp would show a fall of potential of 14 volts, since it has been found that the fall of potential is proportional to the resistance.

Series wiring has certain disadvantages. If one of the lamps shown in the diagram burns out, the others all go

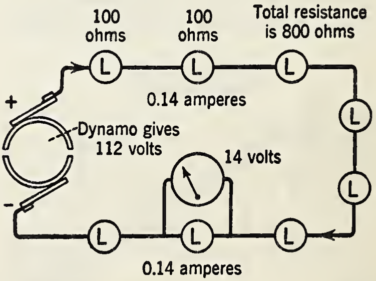

100 ohms
100 ohms
Total resistance is 800 ohms
L
L
L
0.14 amperes
+
Dynamo gives 112 volts
L
14 volts
L
−
L
L
L
0.14 amperes

FIG. 673. The potential drops from 112 volts to zero.

out, because the circuit is broken. Sometimes we would like to have more current flow through one appliance than through another, but this is impossible when they are wired in series. Each appliance *adds* its resistance to the resistance of every other appliance in the same series circuit.

In conclusion: 1. The *total resistance* in a *series* circuit is equal to the *sum* of all the separate resistances.

2. The *current* in *all* parts of a *series* circuit is the *same.*

3. The *fall of potential* in a *series* circuit is *proportional to the resistance.*

**614. What are the results of parallel wiring?** Given two equally good parallel roads between New York and Philadelphia. Normally, each road will carry half the traffic. The congestion, or resistance, will be less than occurs when all the traffic moves over one road. What happens when we have two *parallel* wires through which the electric current can flow? (See Fig. 674.) The current from the positive plate divides at $A$. A part of it flows through the branch $C$ to $B$, and the rest flows through the branch $D$. Let us suppose that each branch of the divided circuit has a resistance of 10 ohms. Then each branch will carry just half of the current. *The total resistance of both branches is exactly half that of each branch.*

The fact that the total resistance of a *shunt or divided circuit* is less than that of any branch usually astonishes the student. It is easy to understand, if he stops to consider, that two parallel water pipes can carry more current than a single pipe, or that traffic congestion is less over parallel streets than when all streets but a single one are closed to traffic. If we wish to empty a large building filled with people, there is less resistance when some use different doors than there is when the entire crowd uses a single exit only.

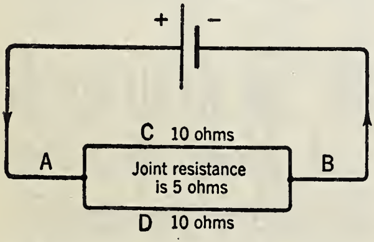


FIG. 674. Parallel circuit, or shunt circuit.

**615. How can we find the total resistance of parallel conductors?** If each of two or more parallel conductors has the same resistance, then their total resistance is $1/n$th that of a single conductor. For example, four wires of 4 ohms resistance each are joined in parallel. Their *total resistance* is $\frac{1}{4}$ that of a single wire, or 1 ohm.

Suppose, however, that we have two wires joined in shunt in a circuit, as in Fig. 675. The resistance, $r$, of one branch is 2 ohms, and the resistance, $r'$, of the other branch is 3 ohms. The *conductance of a wire is defined as the reciprocal of its resistance.* We wish to find the joint resistance, $R$, of both branches.

The total conductance $C = \frac{1}{R}$;

the conductance $c$ of branch $r = \frac{1}{r}$;

the conductance $c'$ of branch $r' = \frac{1}{r'}$.

It follows that $C = c + c'$.

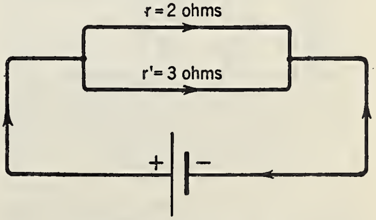


FIG. 675. A shunt circuit.

Whence the formula,

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'}.$$

Substituting the known values, we have

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{3}.$$

Whence, $R = 1.2$ ohms.

Problem. Three wires are joined in parallel. One has a resistance of 2 ohms; another a resistance of 3 ohms; and the third a resistance of 6 ohms. Find their joint resistance.

*Solution.* Substituting in the formula,

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'} + \frac{1}{r''},$$

we have $\frac{1}{R} = \frac{1}{2} + \frac{1}{3} + \frac{1}{6}$. Clearing of fractions, $12 = 6R + 4R + 2R$.

Whence, $12R = 12$, and $R$ equals 1 ohm, the joint resistance.

**616. What proportion of the current does each shunt carry?** If there are two exits of equal width from a building, we would expect the same number of persons to pass out through each exit. Similarly, if the two conductors of a divided circuit have the same resistance, each one will carry half the current.

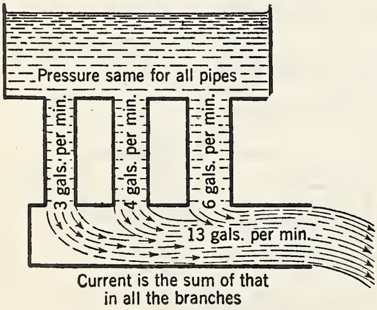

Pressure same for all pipes
3 gals. per min.
4 gals. per min.
6 gals. per min.
13 gals. per min.
Current is the sum of that in all the branches

Fig. 676. The current in the main pipe equals the sum of the currents in all the branches.

Given three parallel water pipes leading from a water tank, and all discharging into the same water main, as represented in Fig. 676. The total number of gallons per minute flowing through the main equals the number of gallons per minute discharged by all the pipes together.

If we have two or more conductors, all having the same resistance, then the amount of current flowing through each branch equals $1/n$th of the total current. Fig. 677 represents 5 lamps of 220 ohms each, all wired in *parallel.* They operate on a 110-volt circuit. Their total resistance is $1/n$th, or $\frac{1}{5}$, of 220 ohms, or 44 ohms. Therefore, the amount of current that will flow in the main circuit is 2.5 amperes. (By Ohm's law. $110 \div 44 = 2.5$.) Each lamp carries $\frac{1}{5}$ of the current, or 0.5 ampere.

Just as more people can pass out through a *wide* door, so more current in a divided circuit flows through the branch of *less* resistance. If one of the two parallel roads between two cities is 40 ft. wide and the other is only 20 ft. wide, we would expect the broad road (less resistance) to carry $\frac{2}{3}$ of the traffic. Suppose that in Fig. 675 the current in the main circuit is 5 amperes; then $\frac{3}{5}$ of the current will flow through the branch $r$ of 2 ohms resistance, and only $\frac{2}{5}$ of the current will flow through the branch $r'$ whose resistance is 3 ohms.

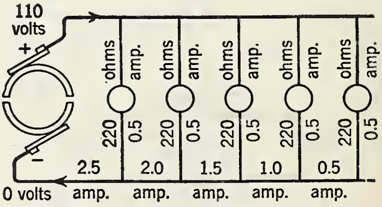

110 volts
+
−
220 ohms
0.5 amp.
220 ohms
0.5 amp.
220 ohms
0.5 amp.
220 ohms
0.5 amp.
220 ohms
0.5 amp.
2.5 amp.
2.0 amp.
1.5 amp.
1.0 amp.
0.5 amp.
0 volts

Fig. 677. Lamps wired in parallel.

PROBLEM. The two branches of a shunt circuit have resistances of 1 and 9 ohms respectively. If 30 amperes of current flow through the main circuit, what current will flow through each branch?

*Solution.* By analysis, the branch that has a resistance of 1 ohm will carry nine tenths of the current, or 27 amperes; the 9-ohm branch will carry one tenth of the current, or 3 amperes.

PROBLEM. Three appliances are connected in parallel on a 110-volt circuit. Their resistances are 22, 44, and 55 ohms, respectively. Find the amount of current flowing through each appliance. (See Fig. 678.) Find the current in the main circuit. What is the joint resistance?

*Solution.* The difference of potential across the terminals of each appliance is 110 volts. Hence, the current in appliance *A* equals 110 ÷ 22, or 5 amperes. (Ohm's law.) The current through *B* equals 110 ÷ 44, or 2.5 amperes. The current flow through appliance *C* equals 110 ÷ 55, or 2 amperes. The current in the main circuit equals the sum of 5, 2.5, and 2, a total of 9.5 amperes. The joint resistance equals 110 ÷ 9.5, or almost 11.6 ohms.

NOTE. Either method of solving such problems as the above may be used. Probably the latter method is the easier one.

In conclusion: 1. The *voltage* across the terminals of all the appliances in a parallel circuit is practically the same.

2. The *current flowing in each branch* of a two-branch circuit is inversely proportional to the resistance of that branch.

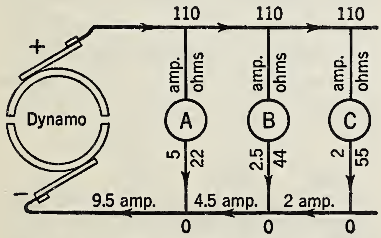


FIG. 678. The current in the main circuit equals the sum of the currents in all the branches.

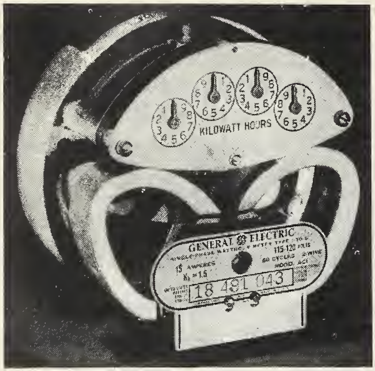
3. The *total current* in the circuit is equal to the *sum* of the currents in all the branches.

4. The *resistance* in each branch and the *total resistance* in the circuit may be found by Ohm's law.

**617. Why is parallel wiring so largely used?** Possibly you use for your Christmas tree small bulbs that are wired in series. If so, you find that when one bulb burns out, the circuit is broken and all go out. Searching for the burnt-out bulb is a nuisance, and it would be most unsatisfactory if all our lamps were wired in series. We would be forced to turn on all our lights at one time, or to have none at all. When lighting bulbs are wired in parallel, one can turn on *any one* or *all* at one time.

If the sockets or outlets in our house wiring system were wired in series, every lamp and every appliance we use would receive the same amount of current. But we need from a fraction of an ampere for our small lamps to 5 or more amperes for a toaster or a flatiron. By having the sockets wired in parallel, we may plug into one socket a floor lamp that draws 0.5 ampere from a 120-volt circuit, and at the same time we can plug into another socket a flatiron that takes 5 amperes. On a parallel circuit, we may use any number of appliances we wish, even if each one uses a different amperage. Fig. 678 shows the amount of current flowing through each of several appliances connected in parallel on a 110-volt circuit, and the amount of current in the main circuit. Each tributary to a river adds to the volume of water in the river, and all the branches of a parallel circuit add to the number of electrons flowing in the main circuit. Every added appliance adds its amperage to that flowing in the main circuit.

## 3. Electric Power and Energy



*Courtesy of the General Electric Company*

Fig. 679. Watt-hour meter for use with alternating current.

**618. What is electric power?** In accord with Faraday's laws, the amount of chemical energy that is stored up in a storage battery depends upon the amount of current used in charging the battery and upon the time that current flows. The *capacity* of a storage cell is usually rated in *ampere-hours*. To illustrate, a battery which has a capacity of 90 ampere-hours can supply a current of 1 ampere for 90 hours, 2 amperes for 45 hours, 3 amperes for 30 hours, etc. Thus we see that it is possible to deliver a small quantity of electrical energy for a long time, or a larger amount of electrical energy for a shorter time. The rate at which electrical energy is delivered is called *electric power.*

*The watt is the unit of electrical power. The watt is equal to a current of one ampere driven by a pressure of one volt.* Hence,

*volts × amperes = watts.*

If the pressure is 1 volt, a current of 1 ampere flowing continuously for *one hour uses one watt-hour* of electrical energy. The consumer buys electrical energy at a certain price per *watt-hour,* or per *kilowatt-hour. One kilowatt-hour equals 1000 watt-hours.* A flatiron operating on a 120-volt circuit uses 5 amperes of current continuously for one hour. It consumes 600 watt-hours (120 × 5) of electrical energy, or 0.6 of a kilowatt-hour.

If we connect a voltmeter across the terminals of a circuit and an ammeter in series, we can find the rate of expenditure of energy in the circuit. The reading of the voltmeter in volts multiplied by that of the ammeter in amperes equals watts. Electric *watt-hour meters* are generally made to record their readings directly in kilowatt-hours. Different types of watt-hour meters are used for alternating and for direct current. (See Fig. 679.)

The right-hand dial of Fig. 680 reads by kilowatt-hours from 0 to 10; the next dial reads by 10's from 0 to 100; the third dial reads by 100's from 0 to 1000. The left-hand dial reads by thousands. The reading shown here is 1642 kilowatt-hours. An employee of the company supplying electricity reads the meter once a month. If this meter had read 1620 the preceding month, then the difference, or 22 kilowatt-hours, would show the amount of electrical energy consumed during the month.

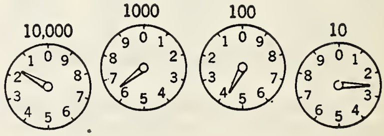


Fig. 680. Kilowatt-hour meter dials.

PROBLEM. A man uses four 40-watt lamps an average of 2 hours daily for one month. He uses two 100-watt lamps an average of 4 hours daily. A bread toaster which has a resistance of 20 ohms is used 20 minutes daily. A flatiron in use a total of 20 hours per month takes 4.5 amperes of current. The voltage is 110. What is his electric bill for one month at a cost of 9 ¢. per kilowatt-hour?

*Solution.* $4 \times 40 \times 2 \times 30 = 9600$ watt-hours for the 40-watt lamps. $2 \times 100 \times 4 \times 30 = 24{,}000$ watt-hours for the 100-watt lamps. $110 \div 20 = 5.5$ amperes. $110 \times 5.5 \times \frac{1}{3} \times 30 = 6050$ watt-hours used by toaster. $110 \times 4.5 \times 20 = 9900$ watt-hours for flatiron. Total consumption is the sum, which is 49,550 watt-hours, or 49.55 kilowatt-hours. The meter reading would be 49 kilowatt-hours, since the fractional part is added to the next bill. At 9 ¢. per kilowatt-hour, the bill would be $4.41.

## 4. Measurement of Resistance

**619. How is resistance measured?** There are several ways to measure the resistance of a conductor. Three methods will be discussed:

1. *Voltmeter-ammeter method.* Look at Fig. 681. We wish to measure the resistance of the conductor *AB*. We connect an ammeter *in series* with the resistance and a voltaic cell and find the number of amperes ($I$) which flow through the resistance. A voltmeter connected *in parallel* across the ends of the conductor enables us to find the potential difference (P.D.) in volts. Then, by Ohm's law,

$$R = \frac{P.D.}{I}.$$

2. *Substitution method.* Let us connect a few constant-voltage cells in series with a sensitive galvanometer and the conductor whose resistance is to be found. After the reading of the galvanometer has been observed, we remove the conductor and substitute for it in the circuit a graduated resistance box. The resistance of the box is then varied enough to cause the galvanometer to show the same reading as before. The conductor must have the same resistance as that shown by the resistance box. (See Fig. 682.)

3. *Wheatstone bridge method.* The Wheatstone bridge consists of a board a little more than a meter in length and about 5 inches in width. (See Fig. 683.) Rather heavy strips of brass are mounted across each end of the bridge and along one side. The brass strip along the side has a gap near one end to permit the insertion of the conductor of *unknown resistance*, *X*, and also one near the opposite end to permit a

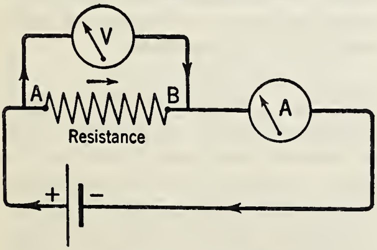


FIG. 681. The voltmeter-ammeter method of finding resistance.

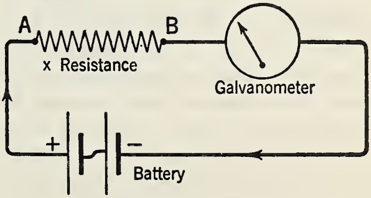


FIG. 682. The substitution method for finding resistance.

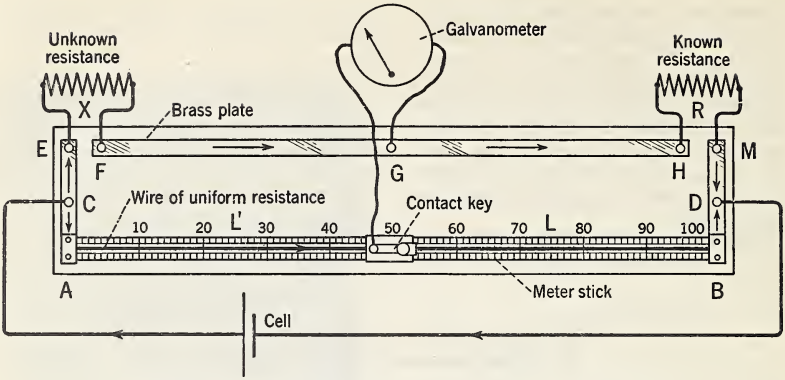


FIG. 683. The Wheatstone bridge is used to measure resistance.

resistance box to be introduced into the circuit. Stretched above a meter stick along the opposite side of the bridge is a uniform wire *AB*. Every unit length of that wire has the same resistance as any other unit length. One terminal of a galvanometer is connected to the binding post, *G*, and the other terminal is connected to the contact key which may be moved along the wire to make contact at any point. Current from the voltaic cell flows to the binding post *C*, where it divides. Part flows along the wire and part along the opposite side of the bridge through both the unknown resistance *X* and the known resistance *R*. The two branches unite at *D* and flow back to the cell to make the circuit complete.

Will any current flow through the galvanometer? If the electrical pressure in the wire at the contact point is exactly equal to that at the binding post *G*, no current flows through the galvanometer. If the pressure at the point of contact made by pressing the key is of higher potential than it is at the point *G*, the current will flow in one direction through the galvanometer. If the pressure at *G* is of higher potential, then the current flows in the opposite direction through the galvanometer. In using the bridge, one slides the contact key along the wire until a point is found where no current flows through the galvanometer. One can tell when such a point is reached because the needle will not show any deflection when the contact key is pressed against the wire at that particular point. This is called *balancing the bridge.* When the bridge is balanced in this manner, then the resistance of the wire $L'$ : resistance $X$ = resistance of wire $L$ : known resistance $R$. But the resistances of $L$ and $L'$ are proportional to their lengths, and their lengths can be read from the meter stick. Suppose that $L'$ is 30 cm. and $L$ is 70 cm. and the known resistance $R$ is 35 ohms. Then,

$$35 : X = 70 : 30.$$

Whence, $X = 15$ ohms. Telephone companies use the Wheatstone bridge to locate a break in the line. It is so accurate that men in the laboratory can tell the linemen between what poles the break is located, even if the poles are miles from the laboratory. This simplifies the task of finding the break.

## Summary

A galvanometer is used to detect the presence of an electric current, to determine its direction, or to measure its pressure and strength. A high-resistance galvanometer calibrated to read volts directly is a voltmeter. A low-resistance galvanometer calibrated to read amperes is an ammeter.

The fall of potential along a conductor is directly proportional to its resistance. An ammeter shows the same reading in one part of a series circuit as in another part.

The joint resistance of several conductors in series equals the sum of the several resistances. When conductors are joined in shunt, the reciprocal of the total resistance equals the sum of the reciprocals of the individual resistances.

By the use of a voltmeter and an ammeter, the resistance of a conductor may be found directly. (Ohm's law.) Resistance may be found by substitution, or by the use of a Wheatstone bridge.

The watt is the unit of electrical power. Volts times amperes equal watts. One kilowatt equals 1000 watts. Power companies usually charge for electrical energy at a certain price per kilowatt-hour.

*How many of the following terms can you define or explain? (We can never get away from measurements.)*

Voltmeter
Resistance coils
Series wiring
Resistance of wires in series
Shunt circuits
Wheatstone bridge
Watt
Ammeter
Fall of potential
Parallel wiring
Resistance of wires in parallel
Electric power
Watt-hour

## QUESTIONS

1. Voltmeters are connected in parallel, and ammeters in series in electrical circuits. Give the reason in each case.

2. Which is more likely to be injured by the heating effects of an electric current, a voltmeter or an ammeter? Explain.

3. Why is a low-resistance conductor generally connected as a shunt across the terminals of an ammeter? Such an instrument is said to be "fool-proof." Explain.

4. Read your electric meter and record its reading. Read it again two weeks later and figure the cost of the electricity used during the two weeks' interval at the current price per kilowatt-hour.

5. New lamp bulbs usually have the power consumption in watts marked upon them. State clearly how you could use a few 40-watt lamps to check the accuracy of your meter.

6. Why must a voltmeter be a high-resistance instrument?

7. Why should an ammeter have a resistance which is practically zero?

8. What do you think would happen to an ammeter if you connected it across the terminals of an incandescent lamp? Explain. (Do not try the experiment.)

9. Why is it necessary to have the coils for resistance boxes made of special alloys?

10. Suppose that an incandescent lamp is made to operate on a 110-volt circuit. How would the lamp be affected by operating it on a 120-volt circuit? How would it be affected if operated on a 100-volt circuit?

11. Most houses are now so wired that the light in the hall may be turned on or off from a switch in the lower hall or by means of a switch upstairs. Study the diagram

shown in Fig. 684 and explain how either switch may operate the light *L*.

12. Suppose that you are planning to introduce an ammeter into a circuit of unknown strength. How could you use a strip of brass plate to prevent burning out the instrument while you are getting some idea as to whether the current is strong or weak?

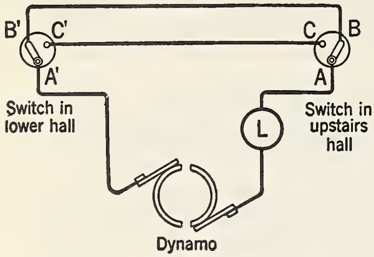


FIG. 684. A three-way lighting switch.

13. Suppose that you are using a three-range ammeter of the type described in Section 609. With which range would you start? If the current is about 2 amperes, with which range would you finish?

14. What piece of apparatus would you use in an arc lamp circuit to reduce the voltage from 120 to 50? Would you connect it in series or in parallel with the arc lamp?

15. What are the disadvantages of series wiring? Has it any advantages?

16. What are the advantages in the use of parallel wiring?

## PROBLEMS

### GROUP A

1. Five incandescent lamps are joined in series in a circuit whose total fall of potential is 550 volts. What is the difference of potential between the terminals of each lamp?

2. If five incandescent lamps are joined in parallel in a circuit whose total fall of potential is 110 volts, what is the fall of potential across the terminals of each lamp?

3. Three wires which have resistances of 4, 6, and 10 ohms respectively are joined in series. What is their joint resistance?

4. Resistance coils of 5, 7, and 13 ohms, respectively, are joined in series with a cell whose E.M.F. is 2 volts. If the internal resistance of the cell is 0.2 ohm, what current flows through the circuit?

5. A flatiron uses 4.5 amperes of current when operating on a 110-volt circuit. What is the cost of operating this flatiron for 4 hours at 10 cents per kilowatt-hour?

6. A coffee percolator has a heating coil whose resistance is 20 ohms. If it is used on a 120-volt circuit 30 minutes a day for 30 days, what will be the cost at 9 cents per kilowatt-hour?

7. A man uses four 25-watt lamps an average of 2 hours daily; he uses eight 40-watt lamps an average of one hour daily; he uses a flatiron like that of Problem 5 a total of 16 hours per month. What is his total bill for a month of 30 days at the rate of 10 cents per kilowatt-hour?

2.235

8. Calculate the joint resistance of the three wires of Problem 3 when they are joined in parallel.

9. Suppose that the coils of Problem 4 are all joined in parallel. What current will flow in the main circuit? Make a diagram before you solve the problem.

### GROUP B

10. Two wires, having resistances of 3 and 5 ohms respectively, are joined in parallel with a battery that has an E.M.F. of 18.75 volts. What current flows in the main circuit? What current will flow in each branch? Make a diagram before attempting to solve the problem.

11. A storage cell, E.M.F. equals 2 volts and internal resistance 0.1 ohm, is connected to the terminals of two coils in parallel. If the coils have resistances of 4 and 5 ohms respectively, what is their joint resistance? What current flows in the main circuit? What current flows in each branch?

12. Suppose that an ammeter whose resistance is 0.009 ohm can carry safely 10 amperes. If it reads 10 amperes when connected in series, what will be its reading after a shunt of 0.001 ohm resistance has been connected across its terminals as in Fig. 685? How strong a current can then be used with the ammeter?

13. A voltmeter connected across the terminals of a dynamo shows an E.M.F. of 110 volts. Three lamps, A, B, and C, each having a resistance of 110 ohms, are connected as shown in Fig. 686. When the lamp C is turned off, what current will flow through the ammeter? What current will flow when the lamp C is turned on? Explain why the lamp A will glow more brightly than either one of the others.

14. Lamps are rated in watts. How many watts does a 16 C.P. carbon filament lamp use if its resistance is 220 ohms and it is used on a 110-volt circuit? How many watts does it use per candle?

15. A tungsten lamp gives 32 candle power. When it operates on a 110-volt circuit, it uses 0.363 ampere of current. How many watts does it use? How many watts per candle? Compare its efficiency with that of the carbon lamp of Problem 14.

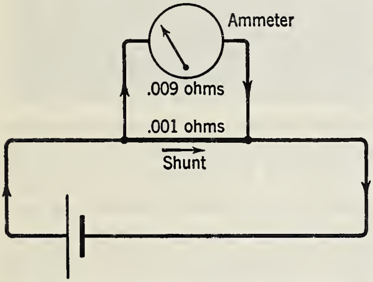


Fig. 685. A shunt across an ammeter.

16. The motor of an electric refrigerator uses 200 watts of electricity. The motor runs an average of 10 hours daily to keep the box cool. At a special power rate of 6 cents per kilowatt-hour, what is the monthly cost?

17. A lamp uses 80 watts when operating on a 120-volt circuit. What is the current consumption in amperes? What is the resistance of the filament? What would be the resistance of three such lamps joined in series? Of three such lamps in parallel?

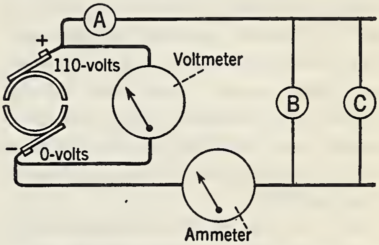


Fig. 686. Series-parallel connection.

# *Induced Currents*

## 1. How a Current Is Produced by Induction

**620. What is electro-magnetic induction?** Oersted proved that a current flowing through a conductor sets up a magnetic field around the conductor. It seems reasonable to suspect that a *magnetic field might be used to produce an electric current.* As early as 1831, Michael Faraday began some experiments to test the *effect of a magnetic field upon a conductor moving through the magnetic field, and of a magnetic field moving so that its lines of force are intersected by the conductor.* (See Fig. 687.)

Let us connect the terminals of a spool of wire to a sensitive galvanometer, as shown in Fig. 688. When we thrust one end of a strong bar magnet down into the spool, the galvanometer needle is deflected. *This shows that a current is induced in the wire by the magnet.* When the bar magnet is withdrawn from the spool, an induced current is set up in the *opposite direction.* If we repeat the experiment, we find that a stronger current is induced by thrusting the magnet into the spool or withdrawing it *more quickly.* When the magnet is *at rest* in the spool, no current is induced. If we use the opposite pole of the magnet, the current directions are just reversed.

Such experiments were first performed by Faraday. He proved that *an E.M.F. is induced in a conductor when a magnet is so moved that its lines of force are intersected by the conductor.* The importance of this discovery can hardly be overestimated. It led to the invention of the dynamo, which supplies current to run our streetcars, our subway trains, and our electric railway trains, to light our houses, to run our refrigerators, washing machines, and vacuum cleaners, and for most commercial purposes where electricity is used.

**621. Current may be induced in a moving conductor.** In the experiment of Section 620 the magnet was so moved that its lines of force were cut by one or more conductors. Let us modify the experiment and thrust a coil or loop of wire down over one of the poles of a horseshoe-shaped magnet. As the coil moves down past the

### Vocabulary

Dynamo, a machine which transforms mechanical into electrical energy.

Alternator, a machine which generates alternating current.

Stator, the stationary part of a generator or motor; it may be either the field or the armature.

Rotor, the rotating part of a generator or motor; it may be either the field or the armature.

Magneto, an electric generator which uses permanent magnets as field magnets.

Alternating current, a current that is continually reversing its direction.

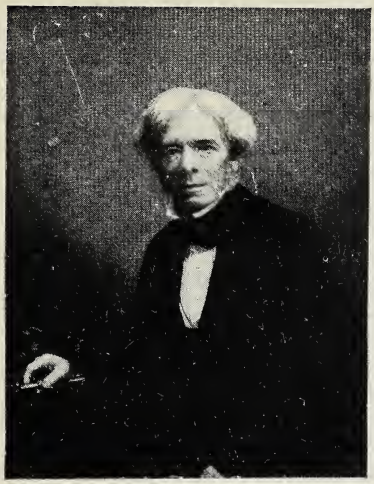


FIG. 687. Michael Faraday (1791–1867) was a distinguished English physicist and chemist. He was assistant to Sir Humphry Davy at the Royal Institution. When Davy was asked what he considered his greatest discovery, he is said to have replied, "Michael Faraday." Faraday liquefied certain gases, formulated the laws of electrolysis, and discovered the principle of electro-magnetic induction which led to the development of the dynamo.

pole of the magnet it cuts or intersects its lines of force and *an induced E.M.F. is set up in the coil.* If the ends of the coil are connected to the terminals of a galvanometer, then we shall have *an induced current set up in the coil,* as shown by the deflection of the needle of the galvanometer. When we quickly remove the coil, then the induced current flows in the opposite direction. We may draw the following conclusion: *An induced current is always set up in a closed circuit when a conductor in that circuit is cutting lines of force.* It makes no difference whether the conductor moves across the lines of force of the magnet, or whether the magnet moves past the conductor. *One or the other must be in motion to produce an induced current.*

We must not fail to distinguish between an *induced E.M.F.* and an *induced current.* If the ends of a coil, as in Fig. 689, are not connected, and the coil is on open circuit, then an *induced E.M.F.* is set up in the coil as it moves across the lines of force, but no current can flow. When the circuit is closed, by connecting the coil to a galvanometer, for example, then we get an *induced current.* An induced E.M.F. has potential energy; when the circuit is closed, its energy becomes kinetic, and an induced current flows through the circuit.

**622. What direction does the induced current take?** When a wire is shoved down between the poles of a horseshoe magnet, as shown in Fig. 690, an induced E.M.F. is set up in

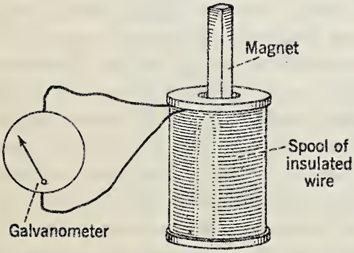


FIG. 688. A magnet cutting lines of force induces an E.M.F.

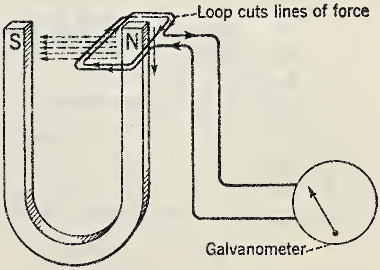


FIG. 689. Electro-magnetic induction. Current induced by moving coil.

the wire. If we close the circuit, an induced current flows. By connecting the ends of the wire to a sensitive galvanometer, it may be shown that the current flows in one direction as the wire moves *down* between the poles of the magnet, and in the reverse direction as it moves *up* through the magnetic field between the two poles. Cutting lines of force in one direction sets up a current in a conductor; when the conductor cuts lines of force in the opposite direction, the current is reversed. When the conductor moves parallel to the lines of force, no current is induced.

The direction in which the induced current flows may be found by the use of the following right-hand rule, which is sometimes called the *dynamo rule: Let the extended fore-finger of the right hand point in the direction of the lines of force; turn the hand so that the extended thumb points in the direction the conductor is moving; the middle finger, bent at right angles to both the thumb and fore-finger, will then point in the direction of the induced current.* Applying this rule to Fig. 690, we find that the current flows toward the observer as the wire moves up between the poles of the magnet; it flows from him as the wire moves down between the poles of the magnet.

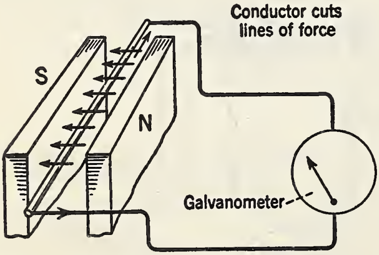


FIG. 690. The conductor cuts lines of force in moving through the magnetic field.

*The Hall rule.* Hold the right hand with the extended fingers pointing in the direction of the magnetic lines of force, as the conductor moves *toward* the palm of the hand. The extended thumb then points in the direction the induced current is flowing.

**623. What is Lenz's law?** In Section 621 we learned that an induced current is set up in a coil of wire as it moves down over the pole of a magnet. Of course, in such a case the coil will become a magnet. The induced current flows in such a direction that the magnetic pole of the moving coil *opposes* the field of the stationary magnet by repulsion. For example, if the coil is moving toward the N-pole of the magnet, the current will flow in such a direction that the face of the loop or helix approaching the N-pole will also become an N-pole. They repel each other, and try to prevent the coil from being lowered over the pole of the magnet. Hence, work is done in overcoming this force of repulsion. When we try to remove the coil, the current reverses. Thus an S-pole is formed; this S-pole attempts to prevent the removal of the coil by its attraction for the N-pole of the magnet. Therefore, work is done in removing the coil. These results may be summarized in a statement known as LENZ'S LAW: *An induced current set up in a moving conductor always flows in such a direction that it forms a magnetic field which opposes the motion of the conductor.* If the reverse were true, then we could create energy. If a dynamo could be built in which the reverse of Lenz's law could occur, then it would produce electricity without any steam or water power to drive it. But whenever an induced current is produced, it is done at the expense of some other form of energy.

If we thrust the coil down over the S-pole of the magnet, the current that is induced will flow in such a direction that the face of the coil approaching the magnet becomes an S-pole and opposes the motion. Lenz's law is merely another example of the fact that we cannot get something for nothing. Mechanical energy is *transformed* into electrical energy.

**624. How great is the strength of the induced E.M.F.?** We have already seen that a higher E.M.F. is induced when a conductor moves rapidly through a magnetic field so that it cuts the lines of force faster. If we use a stronger magnet, there will be more lines of force to cut. Thus the stronger the magnet, the higher the induced E.M.F. When we double the number of loops in the coil, we double the number of conductors that are cutting lines of force. Hence we increase the induced E.M.F. by increasing the number of loops. *The strength of the induced E.M.F. depends upon the number of lines of force cut per second.* Experiment shows that 100,000,000 lines of force must be cut per second to produce an induced E.M.F. of one volt.

In any one of three ways, it is possible to build up a high voltage by induction: *we may increase the strength of the field magnet, increase the speed of a rotating coil, or increase the number of loops in the coil.* In all of these ways, we increase the number of lines of force cut per second.

## 2. Dynamos and Alternators

**625. How is current induced in a revolving loop?** To move a loop of wire up and down in a magnetic field is not a convenient method for producing an induced current. Instead, we may mount the loop on an axis so that it may be turned between the poles of the magnet by steam power or by water power. Fig. 691 shows a single loop of wire mounted on an axis so that it may be rotated by hand between the poles of a magnet; thus it cuts lines of force. Such an arrangement is a simple ideal dynamo. The *field magnet* furnishes the lines of force. The rotating loop, which we may call the *armature*, cuts the lines of force.

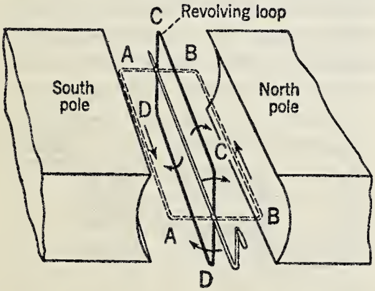


Fig. 691. A simple ideal dynamo with a single rotating loop.

When the crank is turned, one wire of the loop moves down past the N-pole of the field magnet as the other wire moves up past the S-pole. By applying the dynamo rule, we find that the current encircles the loop in one direction during one half-revolution, and in the opposite direction during the other half-revolution. The complete revolution is known as a *cycle*. A current that flows in one direction during part of a cycle and in the opposite direction during the rest of the cycle is called an *alternating current*. When a current flows in one direction only, it is called a *continuous* or *direct current.* The current in the armature of a dynamo is *alternating.*

With such a revolving loop, the E.M.F. rises to a maximum in one direction as one wire of the loop moves up past one pole, and then falls to zero when the wire is moving parallel with the lines of force. See Fig. 692, which represents the E.M.F. of a rotating loop during one complete cycle. As the wire moves down past the other pole, it is cutting lines of force in the opposite direction, and the E.M.F. rises to a maximum in the other direction. The E.M.F. reaches a maximum when both wires of the loop are cutting a maximum number of lines of force, as at *AB,* Fig. 691. When the loop reaches the position shown at *CD,* no lines of force are being intersected, and the E.M.F. is zero.

**626. How is current taken from the armature?** If we were to connect the ends of a revolving loop direct to some instrument, the wires would be twisted off after a few revolutions of the loop. To utilize the current for work in an external circuit, the ends of the loop are soldered to two brass rings, called *slip-rings,* which are mounted on the same shaft as the loop. These rings are carefully insulated from each other so that the current will not short-circuit through the loop. Two metal strips or carbon blocks, called *brushes,* rest lightly on the slip-rings as they revolve with the loop. The brushes are stationary, but they make contact with the rotating slip-rings. The ends of the wires used in the external circuit are connected to the brushes, which take current from the slip-rings and transmit it to the external circuit. (See Fig. 693.)

**627. What is a magneto?** Since 100,000,000 lines of force must be cut per second to give an E.M.F. of one volt, the single loop of Fig. 691 furnishes too feeble a voltage to be of any practical value. In commercial machines, the *armature* consists of a *large* number of loops or coils wound on an iron core. The simple H-armature devised by Siemens consists of a grooved iron cylinder wound with a large number of loops of insulated wire. By rotating such an armature rapidly between the poles of a strong magnet, a high E.M.F. can be obtained. In the *magneto,* several permanent horseshoe magnets are used as *field magnets.* The magneto generates an alternating current which is used extensively for ringing telephone bells, and with a spark-coil for ignition in gas engines.

**628. How does the alternating-current dynamo work?** *The dynamo is a machine for transforming mechanical energy into electrical energy.* It is often called a *generator* or an *alternator.* It builds up a difference of potential between its terminals. Thus it can push

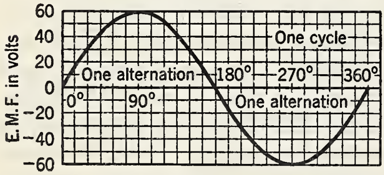


Fig. 692. A curve of the type produced by an alternating E.M.F.

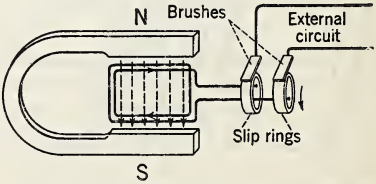


Fig. 693. Slip-rings take alternating current from the armature.

or drive a stream of electrons through the appliances that are connected with it. The simple alternating-current dynamo differs from the magneto in only one important respect: the field magnet consists of a very strong *electromagnet.* A.C. dynamos consist of three essential parts:

1. The *field magnet,* which produces lines of force.

2. The *armature,* which consists of an iron core wound with a large number of coils of insulated wire; the armature revolves on an axis between the poles of the field magnet, and in so doing cuts magnetic lines of force.

3. The *slip-rings* and *brushes.* All dynamos generate *alternating* current in the armature exactly as in the case of the single rotating loop. When this current is taken from the armature by the brushes which rest on the slip-rings, the current in the external circuit is also *alternating;* that is, it flows through the external circuit first in one direction, and then in the opposite direction. Since there are two alternations for each revolution or cycle of the armature, and many commercial machines have a frequency of 60 cycles per second, the number of alternations is 120 per second. For use in heating, lighting, and certain power purposes the alternating current is satisfactory; hence *alternators* are extensively used. For electro-plating or for charging storage batteries, the alternating current cannot be used; it must be changed into a current that is *uni-directional,* or direct.

**629. How does the direct-current dynamo work?** In only one essential does the *direct-current* dynamo differ from the alternator. The terminals of the armature are not connected to slip-rings, but to the segments of a commutator. The *commutator* (*commute,* to change) changes the alternating current of the armature into a current which flows in one direction *only* in the *external* circuit. Such a current is called a *direct* current, a *continuous* current, or even better, a *uni-directional* current, to distinguish it from the *alternating* current. In its simplest form, the commutator consists of a ring of brass which has been split into two semicircular segments, carefully insulated from each other. The terminals of the armature coil are soldered one to each segment, as shown in Fig. 694. Brushes resting on these segments take current from them just as they do from the slip-rings of the alternator.

As the coil of Fig. 694 rotates so that the top wires $AA'$ move toward the observer, the current flows to the commutator segment $C$. The brush bearing on this segment is receiving current; hence it is considered positive. As the armature rotates, the wires $AA'$ of the loop begin to cut lines of force in an opposite direction, as in passing the S-pole they move from the observer. The current then reverses and flows to segment $C'$. But during this rotation of the coil or loop, the segment $C'$ has also moved until it is now in contact with the positive brush. Therefore the brush marked plus always rests on that segment *to* which the current from the armature is flowing. Thus the current is *alternating* in the armature, but *con-*

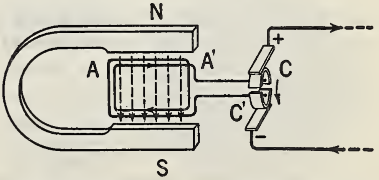


FIG. 694. The commutator changes alternating current to direct current.

*tinuous* in the external circuit. The brushes are so adjusted that the commutator segments change from one brush to the other at the same instant that the current reverses in the armature. While segment *C* is receiving current, it is in contact with the positive brush. While segment *C′* is receiving current, it is in contact with the positive brush.

When only one coil or loop is used in the armature, the E.M.F. is pulsating, or intermittent, as shown in the curve of Fig. 695. To secure a more constant voltage, a large number of coils is used in the commercial dynamo. They are set at angles to one another, so that some coil is always cutting lines of force. It is possible to keep the voltage from varying more than a trifle.

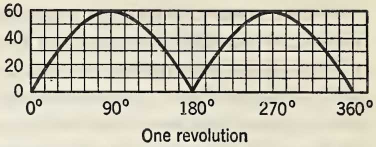


FIG. 695. Direct E.M.F. curve, as produced by a single rotating loop.

## 3. Armatures and Magnetic Fields

★**630. There are two types of armatures in common use.** 1. *The drum-wound armature.* The core of a drum-wound armature is built up of iron discs like that in Fig. 696. These discs are so mounted on an axis that they form grooves in which the insulated wires are wound, first along one groove, then across the end of the drum, and back along the groove on the opposite side. The ends are attached to commutator segments. A large number of coils is used, each coil requiring two commutator segments.

The discs are insulated from one another to prevent *eddy currents* being set up in the iron core by induction. Eddy currents heat the core and cause a waste of energy. The holes in the discs permit the air to circulate through the core to carry away waste heat. Fig. 697 shows men at work building a commercial armature.

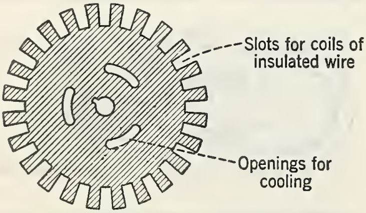
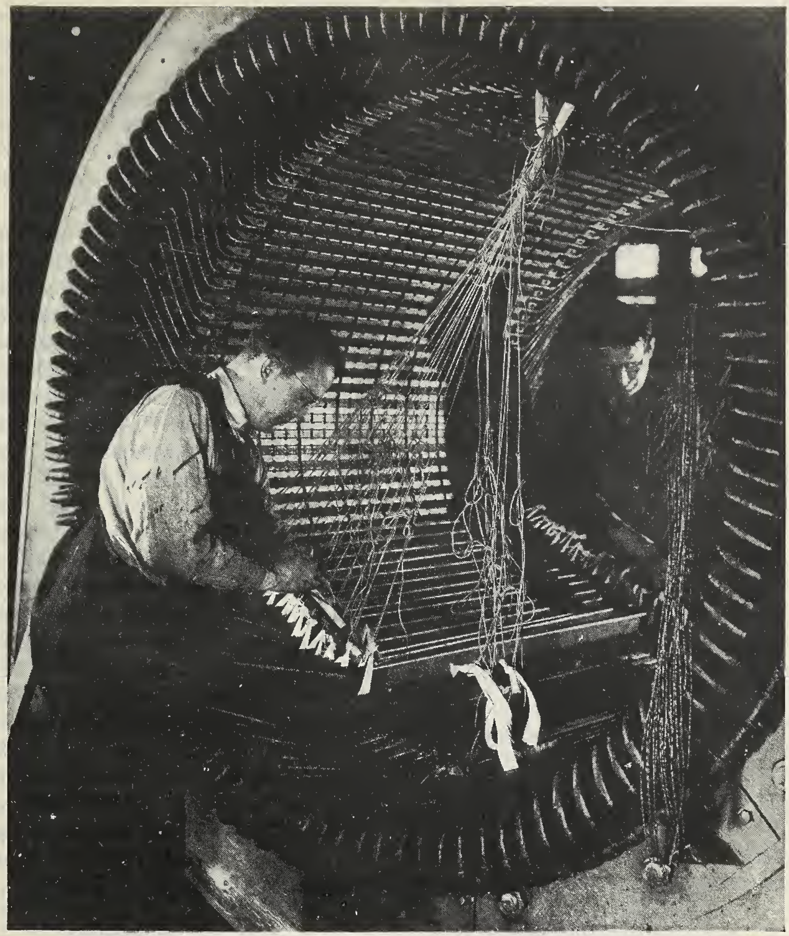


FIG. 696. Slotted disc, for armature core.

2. *Ring-wound armature.* In the *ring-wound armature* the insulated wire is wound in the form of a spiral on an iron ring or shell, as shown in Fig. 698. The wires on the inside of the ring and also those at the ends *do not cut* lines of force. The lines of force follow along the iron ring from one magnetic pole to the other, since the iron is more permeable than the air-gap in the center of the ring. Note the dotted lines of the figure. With the drum-wound armature all the wires except the segments at the ends cut lines of force.

The ring-wound armature wastes wire if used for armatures of small diameter. When an armature of large diameter is drum-wound, much wire is wasted at the ends; in such cases ring-



Courtesy of Westinghouse

FIG. 697. The pupil may get an idea from this figure of the time and work needed for building commercial generators.

winding is less wasteful. It is easier to insulate the winding of the ring type and more convenient to make repairs. The ring-wound armature is not extensively used at the present time.

**631. How is the field magnet magnetized?** In the *magneto*, permanent magnets are used to furnish the lines of force. With the dynamo and alternator, current must be supplied from some source to energize the field magnets. Sometimes the field is magnetized by current from an outside source, a number of storage cells for example. (See Fig. 699.) For *alternators*, a small direct-current dynamo, called an *exciter*, is

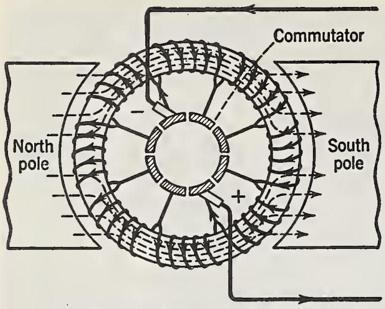


Fig. 698. Ring-wound armature.

generally used for this purpose. By this means the current through the field is kept constant, and the voltage of the alternator does not vary if its speed is uniform. Most *direct-current dynamos* are *self-exciting* machines. They furnish current to energize their own magnetic field.

★**632. Self-exciting machines.** With a direct-current dynamo, a part or all of the current induced in the armature may be conducted through the wires of the field magnet to energize it. Such self-exciting machines are of three different types: (*a*) *Series-wound;* (*b*) *shunt-wound;* (*c*) *compound-wound.* To start a new dynamo, the field must be magnetized by some outside source. When the dynamo stops, the field loses nearly all its magnetism, but enough *residual* magnetism is left in the pole-faces to build up enough voltage to cause an induced current in the armature. This current, or part of it, flows through the wires of the field and energizes the field.

If we study Fig. 700, we see that the wire from one of the brushes is coiled around the cores of the field magnet. Thence it goes to the external circuit. This is a *series-wound dynamo.* If the external resistance of such a dynamo is increased, less current flows through the circuit. This means that less current flows through the field and its strength is decreased. Fewer lines of force are then cut per second, and the voltage falls. If the load is always the same, such a dynamo is satisfactory. It is used when there is little variation in load. It may be used for other work, provided a storage battery can be used to help energize the field.

In the dynamo shown in Fig. 701, we find that two wires lead from the positive brush. One goes out to the *external* circuit. The other is a shunt wire which is wound around the cores of the field magnet and then connected to the negative brush. Thus only a part

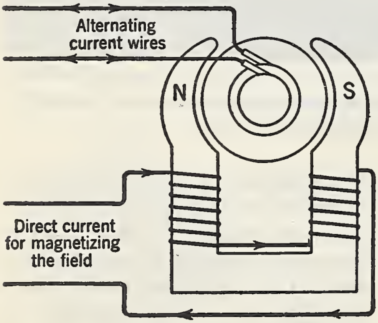

Alternating current wires
N
S
Direct current for magnetizing the field

Fig. 699. The field of an alternator is magnetized by a small dynamo or by a storage battery.

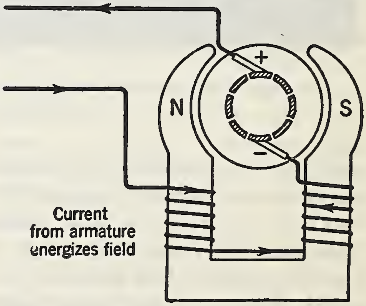


Fig. 700. Series-wound dynamo. Current from the armature flows through the field magnets.

of the current is used to energize the field. This is a *shunt-wound* dynamo. The shunt circuit has many turns of smaller wire. If we increase the resistance of the external circuit, then more current flows through the field, and the voltage of the machine rises.

The merits of the series- and shunt-wound dynamos are combined in the *compound-wound dynamo.* Fig. 702 shows that it is a combination of the two methods of winding just discussed. An increase in the resistance of the external circuit reduces the current in the *series coils,* but it increases the current in the *shunt coils.* It is possible to so adjust the number of coils in each winding that a compound dynamo will give quite a constant voltage, even under varying load.

**633. Compare alternating and direct current.** The *direct current* may be used for heating, lighting, electro-plating, charging storage batteries, electro-magnets, running motors, and practically any kind of electrical work. The chief disadvantage of direct current lies in the fact that there is no practical way to raise its voltage, and its voltage cannot be lowered without introducing resistance and causing a tremendous loss of energy.

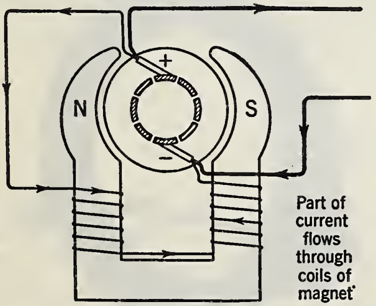


Fig. 701. Shunt-wound dynamo. Part of the current from the armature flows through the field magnets.

The *alternating current* cannot be used for electro-plating or any kind of electro-chemical work. It cannot be used to charge storage batteries without the aid of some charging device. It may be used for running motors, for heating, and for lighting, although it is not so satisfactory as direct current for arc lighting. When it is used to make an electro-magnet, the poles of the magnet are reversed with each alternation. The alternating current has one great advantage over the direct current. The voltage of an alternating current may be raised or lowered just as desired, and there is very little loss of energy during such changes. For long-distance transmission of electrical energy, alternating current is used.

**634. Compare alternators and dynamos.** In commercial dynamos multipolar machines are used. Fig. 703 shows an *eight-pole* field for a direct-current dynamo. The drum-wound armature is shown in position in the magnetic field in Fig. 704. A two-pole field has only one cycle and two alternations per revolution, but a four-pole machine has two cycles and four alternations per revolution. An eight-pole machine has four cycles and eight alternations per revolution. If direct current is needed, the alternating current from the arma-

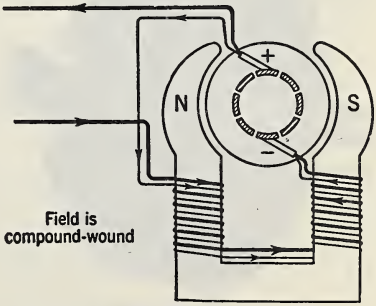
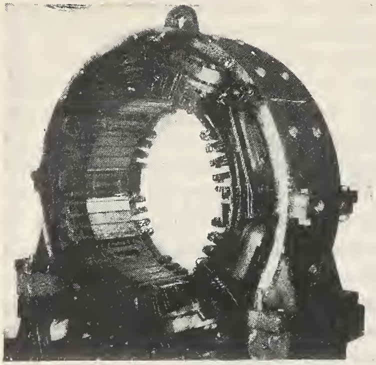
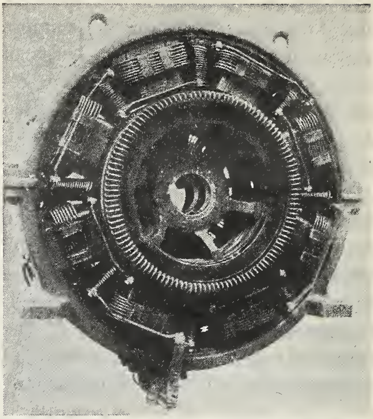


Fig. 702. Compound-wound dynamo.



*Courtesy of Westinghouse*

FIG. 703. An eight-pole field for a D.C. dynamo.

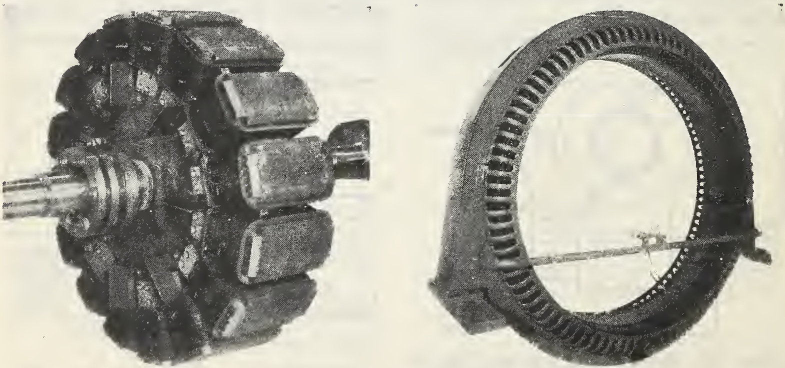


*Courtesy of Westinghouse*

FIG. 704. Armature in field of an eight-pole direct-current dynamo.

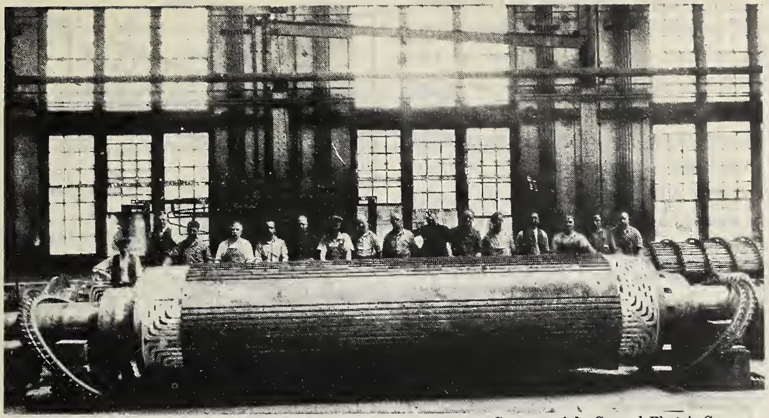
ture must be changed to direct current by means of a commutator. A direct current is not suitable for very high voltages, since it becomes increasingly difficult to insulate the commutator segments as the voltage rises.

For incandescent lighting, an alternator having a frequency of 60 cycles per second is generally used. For power transmission, a frequency as low as 25 cycles per second is commonly used. With 60 cycles there are 120 alternations per second. If we bear in mind the fact that the duration of vision is never less than $\frac{1}{20}$ of a second and that these alternations occur at intervals of $\frac{1}{120}$ of a second, we can understand why there is no flickering in an incandescent lamp. In very high voltage alternators, the armature is stationary, and the field magnet rotates inside the armature. The stationary armature, which is called a *stator*, is shown in



*Courtesy of Westinghouse*

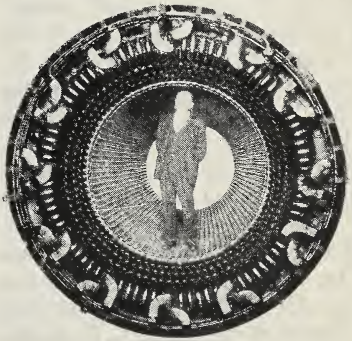
FIG. 705. The rotor and stator of a commercial alternator.



Courtesy of the General Electric Company

FIG. 706. Note the great length of this rotor for a 100,000 KV-A generator which will supply current for a city of 500,000 people.

Fig. 705. The rotating field is called the *rotor*. Since the current is taken from the stationary armature without the use of slip-rings and brushes, the difficulties involved in insulation are decreased decidedly. Figs. 706 and 707 show the rotor and stator of the largest single-unit generator ever constructed. It produces about 133,000 horsepower. One gets some idea of the enormous size of such a generator by comparing the diameter of the stator with the height of the man inside. Note the method of winding of Fig. 706. Try to estimate its length from the number of men.



Courtesy of the General Electric Company

FIG. 707. The stator for the rotor of Fig. 706.

## 4. The Electric Motor

**635. How does the electric motor work?** In construction, the simple direct-current electric motor does not differ essentially from the dynamo. It has one electro-magnet which serves as the field magnet. Another electro-magnet serves as the armature. There is a commutator, and brushes are used, too. *The purpose of the electric motor is to transform electrical energy into mechanical energy.* Current from a dynamo or from some other source is led into the electric motor; there it produces two magnetic fields, one in the field magnet and the other in the armature. The poles of the field magnet mutually attract and repel those of the armature with sufficient force to cause the armature to rotate rapidly. The armature may be geared directly to the machine to be *driven*, or it may have a belt wheel attached to its shaft. Then almost any type of machine may be driven by means of a belt.

**636. What makes a motor run?** To understand the principle of the electric motor, let us mount an electro-magnet on an axis so that it is free to rotate between the poles of a magnet. (See Fig. 708.) If we pass current through the electro-magnet in such a direction that the pole at the top of the figure is an S-pole, it will be attracted by the N-pole of the stationary field magnet and repelled by the S-pole. Its N-pole at the opposite end is attracted by the S-pole of the field magnet and repelled by the N-pole. All these forces are working together to turn in a counter-clockwise direction the electro-magnet which serves as an armature. It would stop when the two sets of opposite poles are nearest each other, if it were not for its inertia, which carries the N-pole, for example, slightly beyond the S-pole of the magnet. If *at that particular instant* the direction of the current flow in the rotating magnet is reversed, then its poles will be reversed. (See Fig. 709.) The stationary poles of the field will then continue to drive the rotating magnet through 180° of rotation by their attraction and repulsion. Another change in the direction of the current and another reversal of the poles will turn the armature through another half-circle. A commutator is used to change the direction of the current flow at just the right instant.

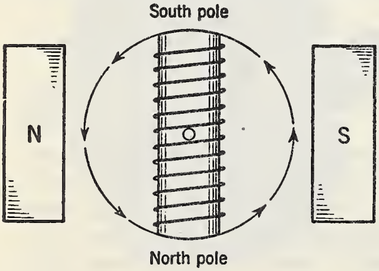


FIG. 708. The armature rotates between the poles of the field magnet.

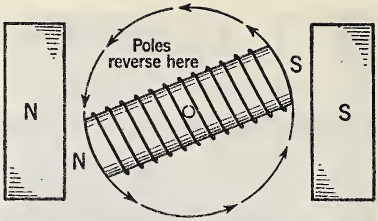


FIG. 709. The current changes direction and reverses the polarity of the armature.

Look at Fig. 710. As the current flows through the armature loop in a counter-clockwise direction, the loop becomes a magnet with its N-pole facing you, and its S-pole on the far side of the loop. The N-pole of the field magnet repels the N-pole of the loop and attracts its S-pole. The S-pole of the field magnet at the same time attracts the N-pole of the loop and repels its S-pole. The two forces of attraction and the two forces of repulsion all *work together* to turn the loop

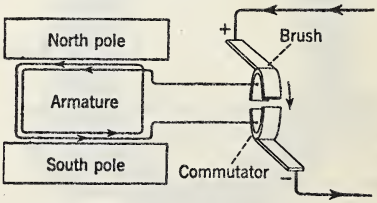


FIG. 710. The commutator is used to reverse the current in the armature of a motor.

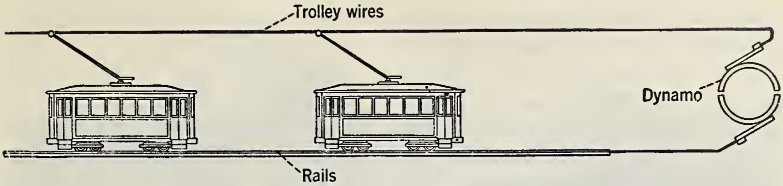


FIG. 711. Streetcars are operated in parallel.

in the direction shown by the arrow. If the current continues to flow in the same direction, the loop will stop rotating as soon as its poles are opposite the corresponding unlike poles of the field magnet. At about the time that point is reached, the commutator reverses the direction of the current in the loop and its polarity is reversed. Then the attraction and repulsion continue as before. Inertia carries the poles past the points of dead center.

The direction of rotation may be found by the use of the *left-hand rule,* or *motor rule.* Extend the fore-finger of the *left* hand in the direction of the lines of force; turn the middle finger, bent at right angles to both the thumb and fore-finger, so that it points in the direction of current flow. The extended thumb then points in the direction of rotation.

The *torque,* or tendency to produce rotation, of a motor armature depends upon the strength of the current and upon the winding of the field and armature; since the strength of an electromagnet depends upon the number of ampere-turns, the torque or twisting force of the armature depends upon the mutual attraction and repulsion of the field magnet and the armature.

**637. For what are series and shunt motors used?** Direct-current motors may be shunt-wound or series-wound. *Shunt motors* are extensively used in machine shops since their speed is not much affected by varying loads. *Series motors* are used on automobiles and streetcars. The torque of a series motor is much greater at starting than that of a shunt motor. Hence the series motor is used when a motor must start under load. In streetcar motors, the armature is connected with the load by means of gear wheels, which at the same time reduce the speed. A series motor is the only type that runs well on either direct or alternating current. Hence it is used extensively in small motors for turning fans, vacuum cleaners, sewing machines, etc. The current reverses in the field at the same time as in the armature; hence such a motor will run on alternating current. They are sometimes called *universal* motors. Streetcars are generally operated at a voltage of 550. The current is supplied to the motor from a trolley wire or a third rail. The current flows through the car wheels to the track, which forms the return circuit, Fig. 711. The Virginian electric locomotive is shown in Fig. 712.

**638. How do alternating-current motors work?** Of the several types of alternating-current motors that are in use, only one type will be discussed. The *induction* motor consists of two parts; the *stator,* which differs little from the stator of an alternator in the manner in which it is wound; and the *rotor,* which is built of copper bars laid in slotted, laminated iron cores. In the

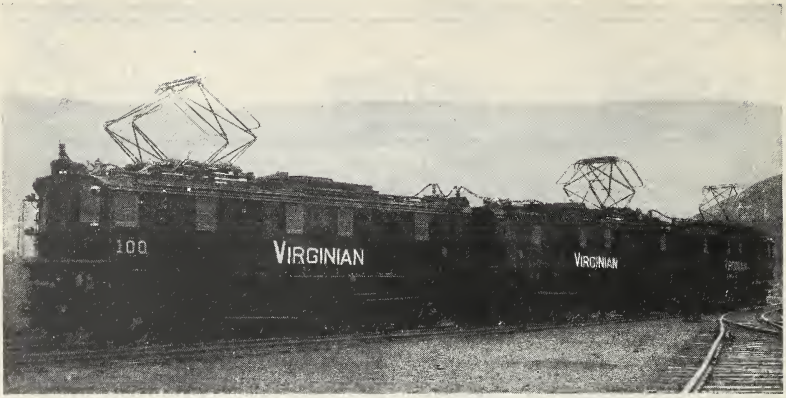
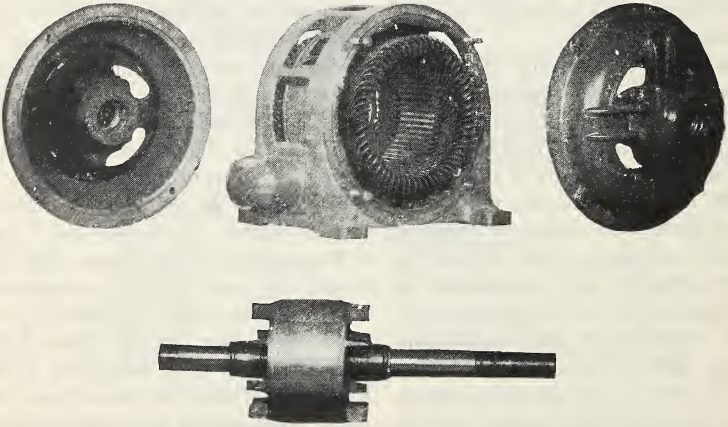


FIG. 712. The largest electric locomotive in the world. Its length is 152 ft., and its weight is 637.5 tons. Its maximum horsepower is 7125, and it can pull with a force of 115 tons. In hauling heavy trains over the Allegheny Mountains, the armatures of the motors generate current on the down grade. Thus they act as a brake and they also supply some current to the line.

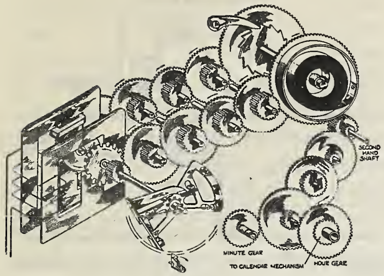
type known as the *squirrel-cage rotor*, the copper bars are all connected at each end to copper rings, Fig. 713. When an alternating current passes through the windings of the stator, a rotating magnetic field is set up. The rotor is not connected in any way to the stator or the electrical supply, but the rotating magnetic field produces a current in the rotor by induction. The magnetic field set up in the rotor by this induced current is dragged after the rotating magnetic field in the stator. Thus the rotor turns very rapidly on its axis. Induction motors are made in all sizes; their advantage lies in their simplicity.

Induction motors find use in some



*Courtesy of the General Electric Company*

FIG. 713. The squirrel-cage induction motor is much used on alternating currents.



*Courtesy of Hammond Instrument Company*

Fig. 714. The electrical impulses of the alternating current operate the clock mechanism. Such clocks are very accurate. Note the interesting trains of gear wheels used to vary speed.

electric clocks, for which they furnish the motive power. Such clocks, operating on alternating current, are very accurate. The gear wheels of Fig. 714 show the clock mechanism.

**639. Back E.M.F. is developed by a motor.** Suppose we connect an incandescent lamp in series with a small motor on the lighting circuit. If the armature is held so that it cannot rotate, the lamp glows brightly. When the armature is released, the light will grow dimmer as the motor comes up to full speed.

The voltage from the lighting circuit is *impressed* upon the motor. When the armature of the motor rotates in the magnetic field of the motor, it is cutting lines of force and producing an E.M.F. As one would infer from Lenz's law, this E.M.F. produced by the motor is a *back E.M.F.*, or a *counter E.M.F.* The back E.M.F. opposes the impressed E.M.F. The *effective* voltage which drives the motor is equal to the *difference* between the impressed E.M.F. and the back E.M.F. Thus we see that *every motor when running is also a generator.*

If a motor whose resistance is only 5 ohms is attached to a 110-volt circuit, 22 amperes of current will flow through the armature when it is at rest. If the same armature, when running at full speed, cuts lines of force fast enough to produce a counter E.M.F. of 100 volts, then the effective voltage is equal to 110–100, or 10 volts. The resistance does not change, but now only 2 amperes of current will flow through the armature of the motor.

Thus we find that the back E.M.F. of a motor which is running without load must be almost equal to the impressed E.M.F. Just enough current flows through the motor to overcome friction. If the armature slows down under load, then the back E.M.F. falls and more current flows through the armature. Thus a motor adjusts itself to a varying load. Motors are *more economical* than other electrical appliances, heating appliances for example, because the counter E.M.F. reduces the amount of current and the power consumption.

**640. How should we start motors?** The resistance of a motor armature is very low. For that reason, there is a sudden rush of current through a motor armature when current is turned on suddenly. Small motors have so little inertia that they come up to speed quickly. They can carry without injury the *temporary overload* that occurs before the armature is brought up to speed and develops a back E.M.F. The armatures of large motors come up to speed slowly, and they are likely to be "burnt out" if the full current is turned on without bringing the motor up to speed first. In the starting of large motors, rheostats are generally used in order to protect the armature. Several coils of resistance wire are connected in series with the motor. As the speed of the motor increases, the resistance is cut out gradually. Fig. 715 shows how it is possible to cut out of the circuit one coil after another by shoving the lever *L* to the right.

In starting a *shunt-wound* motor, the resistance in the field is increased as the resistance in series with the armature is gradually reduced. In Fig. 716, if the lever *L* is moved to the right, one coil after another is cut out of the armature circuit and added to the field circuit. Both of these operations increase the amount of current flowing through the armature and thus increase the speed of the motor.

**★641. What are circuit breakers?** Sometimes an overload may decrease the speed of a motor suddenly. If that happens, a sudden rush of current through the armature may ruin it. To prevent injury to motors, an automatic circuit breaker opens the circuit when such an overload occurs. If the motorman on a trolley car cuts out resistance too rapidly when a car is picking up speed, an automatic breaker opens the circuit with the sharp report that is familiar to all. The motorman then throws in more resistance and closes the circuit again by means of a small lever. When too much current flows through the coil of Fig. 717, the iron core is pulled up into the coil to release the catch and break the circuit.

*Underload circuit breakers* are also in use. A small electric generator driven by the engine of an automobile is used to charge the car's storage battery. An underload circuit breaker is used to disconnect the storage battery from the generator until the voltage of the generator rises to such a point that it is greater than the back voltage of the battery. The battery voltage may be

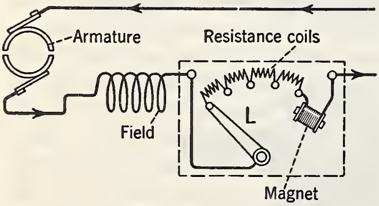

Armature
Resistance coils
L
Field
Magnet

Fig. 715. The starting box diagram for a series-wound motor.

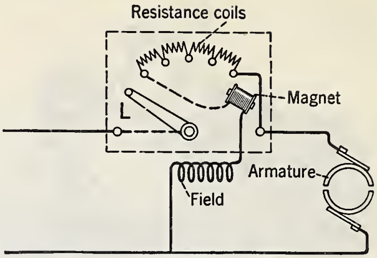

Resistance coils
Magnet
L
Armature
Field

Fig. 716. Starting box wiring, for shunt-wound motor.

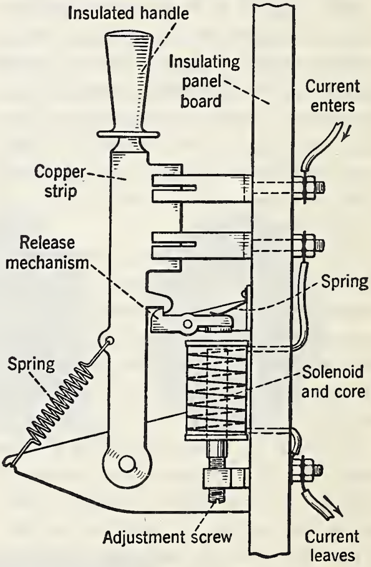

Insulated handle
Insulating panel board
Current enters
Copper strip
Release mechanism
Spring
Spring
Solenoid and core
Adjustment screw
Current leaves

Fig. 717. When too much current flows through the coil, the iron core is pulled up into the coil. It releases the catch so that the spring throws the switch and breaks the circuit.

6 volts or a little more. When the generator is operating fast enough to produce a voltage higher than the usual 6 volts, then the generator is automatically connected with the battery and begins to charge it. Thus the underload circuit breaker prevents the battery from discharging back through the generator. It breaks the circuit again when the engine slows down and the voltage falls below a predetermined value. An *overload circuit* breaker also disconnects the battery so it will not overcharge when the car is traveling at very high speeds. A circuit breaker is also used in place of fuse wires for protecting the wiring circuits of modern automobiles.

## Summary

An induced E.M.F. is produced in a conductor when it cuts lines of force. The induced current set up in a closed conductor cutting lines of force opposes the motion of the conductor through a magnetic field. Its strength depends upon the number of lines of force cut per second. An induced E.M.F. of one volt is produced when 100,000,000 lines of force are cut per second.

The dynamo transforms mechanical energy into electrical energy. The current in the armature alternates twice during each revolution. By means of a commutator, the alternating current produced in the armature may be converted into a uni-directional current in the external circuit.

The armature of a dynamo may be ring-wound or drum-wound. The field magnets may be excited by means of an independent current, or the machine may be self-exciting. A self-exciting machine is series-wound, shunt-wound, or compound-wound.

The electric motor transforms electrical energy into mechanical energy. Since it cuts lines of force it also produces an induced E.M.F., which opposes the E.M.F. from the line wire.

*How many of the following terms can you define or explain?* (*Our commercial electricity is produced by induction.*)

Electro-magnetic induction
Induced E.M.F.
D.C. dynamo
Field magnet
Armature
Self-exciting machines
D.C. *versus* A.C.
Series and shunt motors
Back E.M.F.
Direction of induced current
Alternator
Brushes
Slip rings
Commutator
Eddy currents
Electric motor
A.C. motors
Circuit breaker

## QUESTIONS

1. Why is it impossible to charge a storage battery by using an alternating current?

2. A ship having an iron mast sails east. A wire running along the mast is connected at the top and bottom so that it makes a loop with the mast. Is an induced current set up in the wire? Is an induced E.M.F. produced? Does it matter whether the plane of the loop is coincident with or perpendicular to the earth's magnetic field?

3. Do you think that there would be an induced current set up by a loop of wire revolving on a vertical axis in the earth's magnetic field? Explain.

4. What advantage has the magneto over the dynamo? What advantage has the

self-excited dynamo over the magneto?

5. Some years ago the following query was sent to a scientific magazine: "I have a $\frac{1}{2}$ H.P. hand dynamo. It turns easily until I connect the dynamo with my motor; then it turns hard. What is the matter with my dynamo?" How would you answer this query?

6. Explain in detail why the armature of an electric motor rotates continuously.

7. Compare the cost of running a vacuum cleaner or an electric fan with that of operating an electric flatiron or toaster.

8. Make a list of as many household appliances as you can that make use of the electric motor.

9. Why is a series-wound motor used with the self-starter of an automobile?

10. Why are both starting boxes and automatic circuit breakers needed for use with large motors?

11. Since the amount of current flowing through street car rails is almost the same as that flowing through the trolley wire, why do we receive a more severe shock by touching the trolley wire?

## PROBLEMS

### Group A

1. An electric fan operating on a 110-volt circuit uses 1 ampere of current. What will be the cost of operating this fan for 10 hours at 9 cents per kilowatt-hour?

2. An electric refrigerator has a motor that uses 150 watts of electrical power. What is the horsepower of its motor? If this motor runs an average of 10 hours per day for 30 days, what will be the cost of operating it at a power rate of 5 cents per kilowatt-hour? How do you think this compares with the cost of natural ice?

### Group B

3. A motor operating on a 110-volt circuit develops a back E.M.F. of 90 volts. The resistance of the armature is 4 ohms. What current will flow through the motor? What will be the cost of operating this motor for 10 hours at 10 cents per kilowatt-hour?

4. A motor operating on a 110-volt circuit develops a back E.M.F. of 70 volts. If it draws 10 amperes of current, what is the resistance? What will it cost to operate this motor 10 hours daily for one month at a rate of 7¢ per kilowatt-hour for the first 50 kilowatt-hours, 5¢ for the next 100 kilowatt-hours, and 3¢ per kilowatt-hour for the remainder?

5. How many feet of No. 18 wire ($K$ = 700) will be needed for a flatiron of 22 ohms resistance? If the flatiron weighs 3 kgm., how long must it be connected to a 110-volt circuit to heat it from 20° C. to 180° C.?

4 ohms.

# *Electro-Magnetic Induction*

## 1. Induction Caused by Varying a Magnetic Field

**642. How can a battery current produce an induced current?** The secondary coil of Fig. 718 consists of a large number of turns of fine insulated wire wound on a large wooden spool. Its terminals are connected to a simple galvanometer. Let us place inside this secondary coil a *primary coil,* which has a few turns of coarse insulated wire wound upon a small spool. The primary coil is then joined in series with a contact key and a dry cell.

When the contact key is pressed to *close* the circuit, a current flows through the primary coil. The galvanometer needle is deflected, showing that a current is *induced* in the secondary coil. The lines of force produced by the current flowing in the primary coil *cut across* the wires of the secondary coil and set up an induced current in the secondary. If the key is held firmly, the induced current soon stops flowing. When we release the key and *break* the circuit, a current is *induced* in the secondary, but in the *opposite* direction. Upon closing the circuit, the magnetic field caused by the current flowing through the primary coil rises to a maximum strength, and the lines of force threading across the secondary coils cause the induced current. Upon breaking the circuit, the strength of the magnetic field quickly falls to zero and an induced current flowing in the opposite direction is set up. *We must conclude that increasing or decreasing the number of lines of force in a magnetic field induces an E.M.F. in a conductor present in that field.* If the circuit is closed in the secondary, then an *in-*

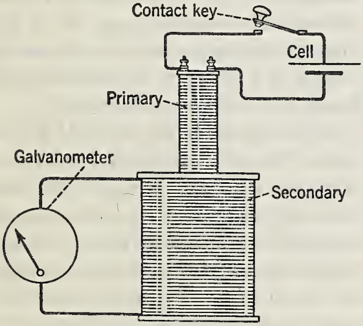


FIG. 718. Varying the strength of the current in the primary induces an E.M.F. in the secondary coil.

### Vocabulary

TRANSFORMER, usually refers to a device for changing the voltage of an alternating current.

RECTIFIER, a device used to change alternating current to direct current, or the reverse.

REACTANCE, a choking effect due to self-induction; inductive resistance.

IMPEDANCE, the joint effect of reactance and resistance in alternating current circuits.

INTERMITTENT, flowing and stopping periodically.

UNI-DIRECTIONAL, always flowing in the same direction.

CHOKE COIL, a coil of high impedance.

*duced current* is produced. The current in such a case is intermittent, since no current is induced unless *the strength of the magnetic field is varied.*

**643. What is the purpose of the induction coil?** It would be irksome to try to produce induced current for any considerable length of time by joggling a contact key up and down as described in Section 642. It is far more convenient to substitute for the contact key a vibrator which "makes" and "breaks" the primary circuit automatically. Then we have the essentials of a *spark coil* or an *induction coil.* The vibrator of the induction coil of Fig. 719 is very similar to the armature-vibrator of the electric bell.

Current flows from the positive plate of the voltaic cell through the heavy wire of the primary coil and returns to the negative plate of the cell through the vibrator, and also the post. The primary coil consists of a few turns of coarse insulated wire wound on a bundle of iron wires, insulated from each other to prevent *eddy currents.* The secondary coil is made up of thousands of turns of insulated wire wound on a spool which surrounds the primary coil. For some commercial coils, miles of fine wire are used in making the secondary coil.

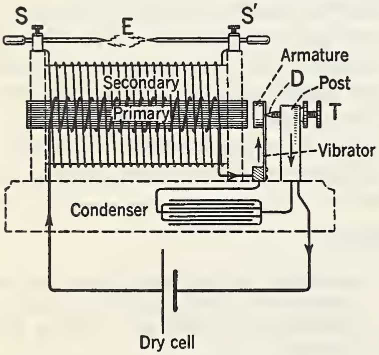


Fig. 719. An induction coil is used to increase the voltage of an intermittent direct current.

When the circuit is closed, the current flows through the primary coil and magnetizes it. Then the armature is attracted and pulled away from the contact screw, *T*, thus breaking the circuit. The magnetic field in the primary decreases in strength rapidly, and an induced E.M.F. of high voltage is set up in the secondary coil. But the core of the primary loses its magnetism when the circuit is broken, and the spring of the armature which serves as a vibrator "makes" or "closes" the circuit. As the magnetic flux in the primary rises to a maximum, an E.M.F. of opposite direction is induced in the secondary. As the vibrator alternately makes and breaks the current flowing in the primary, an *intermittent* E.M.F. is induced in the secondary. The voltage may be so high that an electric spark leaps across the air gap at *E* between the two terminals, *S* and *S′*, of the secondary coil.

The magnitude of the E.M.F. produced in the secondary depends: (*a*) upon the rate at which the magnetic field varies; (*b*) upon the strength of current in the primary; and, (*c*) upon the number of turns in the secondary as compared to the number of turns in the primary. Since the "break" of the current is so much more sudden than the "make," the induced E.M.F. is usually about 10,000 times as high when the "break" occurs.

A condenser is almost always used with such an induction coil. It is connected as in Fig. 719, so that the break comes between its terminals. The inertia of the current gives it a tendency to follow the armature and leap across the air gap at *D* as the break occurs.

When a condenser is used, this energy surges into the condenser; the break becomes much more sudden, and the induced E.M.F. is increased. The spark at *E* is thus made thicker and longer. The condenser, immediately after the current is broken, discharges back through the primary coil. Thus it helps to demagnetize the core.

**644. What are some uses of the induction coil?** Because a high voltage is induced in the secondary of an induction coil, an electric spark occurs between its terminals when they are adjusted to the proper distance. In the automobile, the secondary coil is connected to the spark plugs of the engine. The primary is in series with the storage battery and an automatic circuit breaker. Thus the coil raises the voltage to produce the spark needed to explode the mixture of gasoline and air. The induction coil finds use in the *telephone* and for the operation of *X-ray tubes*. It is also used in some so-called medical batteries.

## 2. Voltage Transformer and Power Transmission

**645. How does the voltage transformer work?** Let us connect the primary of an induction coil to some source of *alternating current*, a magneto for example. Then an induced E.M.F. is set up in the secondary coil without the aid of a vibrator. The alternating current, in rising to a maximum in one direction and then falling to zero, *varies the strength of the magnetic field* around the primary, and thus induces an E.M.F. in the secondary. Then it rises to a maximum in the opposite direction and later drops to zero, thus inducing an *opposite* E.M.F. in the secondary.

The *voltage transformer* is a modified induction coil with the vibrator eliminated. It consists of a laminated iron ring with a few turns of heavy insulated wire coiled around one section, and a large number of turns of smaller wire wound around another section. (See Fig. 720.) If the terminals *AB* are connected to an alternator, an induced current is set up in the secondary coil. The E.M.F.'s in the primary and in the secondary have the same ratio as the relative number of turns of wire in the coils. For example, if there are 20 turns in the secondary for every turn in the primary, the E.M.F. in the secondary will be *twenty times as high* as that in the primary. An alternator which has a voltage of 110 will, if attached to the primary, produce a voltage of 2200 in the secondary. A transformer which raises the voltage in such a manner is called a *step-up transformer*. By reversing the connections, we have a *step-down transformer*. For example, if an alternator which has a voltage of 110 is connected to the secondary coils of the transformer just described, then the voltage in the primary is reduced to only 5.5 volts.

There is no gain in energy in a transformer, because the amperage is re-

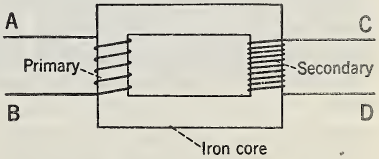
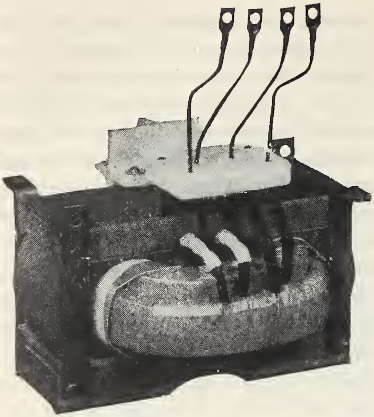


FIG. 720. A transformer diagram.



*Courtesy of the General Electric Company*

Fig. 721. Commercial transformer, with housing removed.

*Courtesy of the Union Pacific Railroad*

Fig. 722. Insulation towers for high-voltage transmission of power. Note the "petticoat" type of insulator.

duced as the voltage is increased. The transformer is one of the most perfect machines ever devised. It does its work silently, with little or no attention, and with an efficiency far higher than that obtained with most machines. From 2% to 5% of the energy may be transformed into heat, so the efficiency varies from 95% to 98%. In the commercial transformer, the two coils are generally concentric. Fig. 721 shows a section of a commercial transformer. To secure better insulation and to absorb the heat, the coils are submerged in oil. Enclosed in an iron box or case, the transformer is mounted on electric poles or it is placed in an underground compartment so that animals will not be killed by coming into contact with the high-voltage terminals.

**646. Why is alternating current used in power transmission?** Because one can change the voltage of an alternating current at will by means of a transformer, it is much cheaper to transmit electrical power by alternating current than it is by direct current. Let us take one example. Suppose one wishes to transmit 1200 kilowatts of electrical energy a distance of some 100 miles. If it is to be transmitted at a pressure of 12,000 volts, then 100 amperes are required. ($12{,}000 \times 100 = 1{,}200{,}000$ watts, or 1200 kilowatts.) If the voltage were increased to 60,000 then only 20 amperes of current would be required. Let us see how the heating effects would compare in the two cases, if we assume that the resistances of the transmission wires are the same. Transmitting at 100 amperes in one case, and at 20 amperes in a second case, we find that the heating effects are proportional to $(100)^2$ and to $(20)^2$. The ratio is 25 : 1. In other words, the heating effect is 25 times as great at 100 amperes as at 20 amperes. More energy is wasted in transmitting at low voltage when the amperage is high than at high voltage and low amperage.

High-voltage transmission means lower amperage, and rather small wires can be used for such transmission lines. Of course, the smaller wires in-

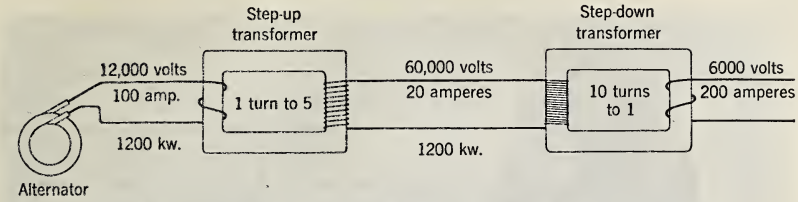
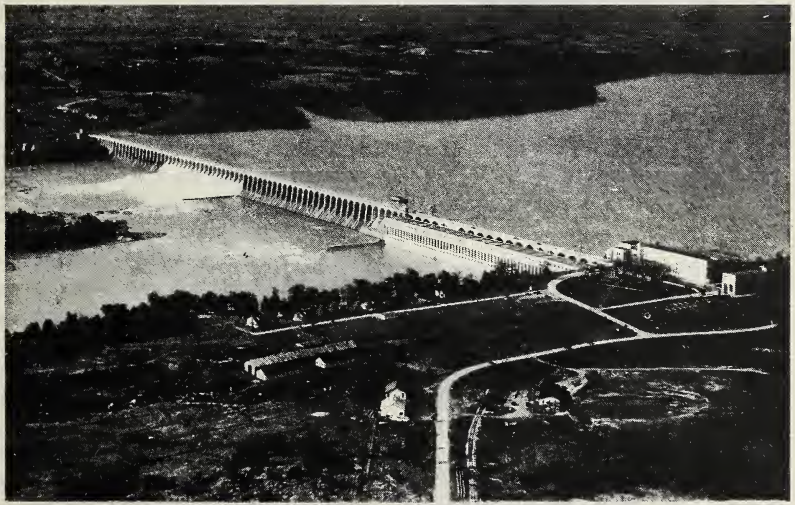

Step-up transformer
Step-down transformer
12,000 volts
100 amp.
1200 kw.
1 turn to 5
60,000 volts
20 amperes
1200 kw.
10 turns to 1
6000 volts
200 amperes
Alternator

FIG. 723. Schematic diagram to show how alternating current is transmitted.

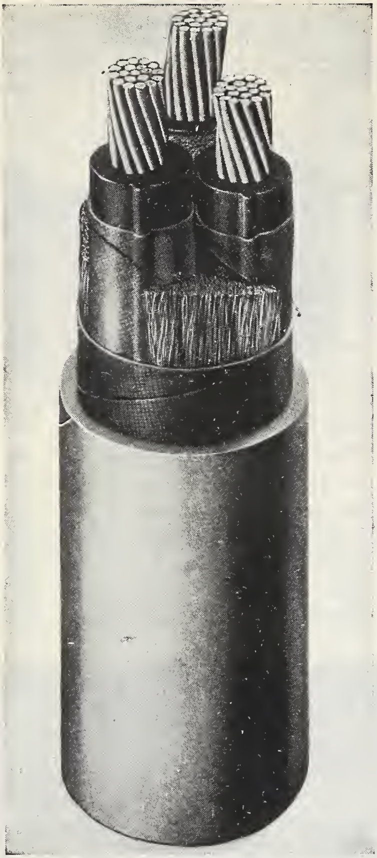
crease the resistance to some extent, but they represent a saving in the initial cost of installation and the stress on the supporting towers is decidedly less. Transmission wires are attached to petticoat insulators which are suspended from the tower arms. (See Fig. 722.) Because insulators are more efficient when dry, the petticoat insulator is so constructed that some portions protect other portions and tend to keep them from becoming wet during a storm. Thus the insulators tend to prevent, to a large extent, leakage from the wires through the towers to the earth.

The voltage of *direct current* cannot be varied without tremendous losses by the use of resistance coils. Hence, it is customary to use *alternating current* when electrical energy is to be transmitted long distances. The practice is to use an alternator to generate the current, to step-up the voltage by means of a transformer, and then to transmit the energy at high voltage to some distant station, where it is stepped-down to the voltage needed



*Courtesy of the Tennessee Valley Authority*

FIG. 724. This Government project aims to develop power from the waters of the Tennessee River. It also aims to prevent the loss of soil by erosion. Hence this dam not only yields power at low cost, but it is an aid in conservation, too.



*Courtesy of the Okonite Company*

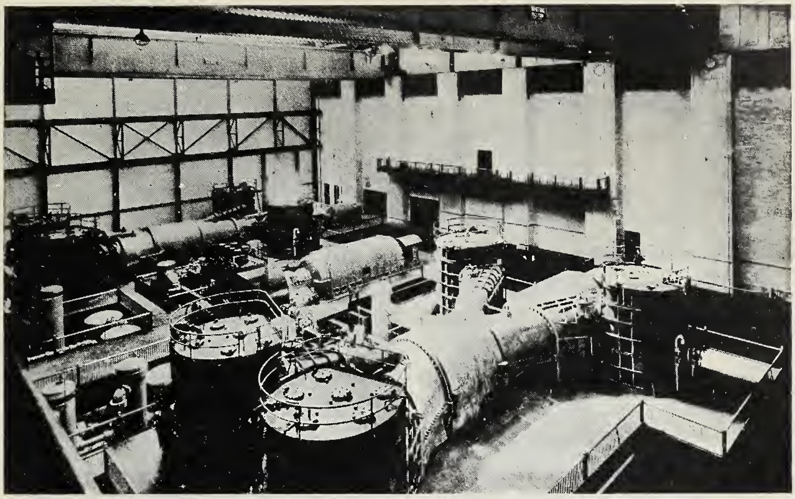
FIG. 725. Section of an insulated power cable.

to operate the appliances for which it is to be used. (See Fig. 723.) In this case, electricity is generated at 12,000 volts, stepped-up to 60,000 volts, transmitted, and then stepped down to 6000 volts. Another transformer may be used to reduce the voltage to any amount that is desired. One high-tension line now transmits electrical energy at a pressure of 220,000 volts from Big Creek to Los Angeles, a distance of about 240 miles. (See Fig. 724.) Power from Boulder Dam is transmitted at 287,000 volts.

A small town that operates its own lighting plant generally produces alternating current at a pressure of 2200 volts. It is transmitted to the consumers and then stepped down to about 110–120 volts before it enters dwelling houses or other buildings. Small transformers are used for ringing doorbells or for operating Christmas tree lights. They step down the voltage from the house circuit to from 7 volts to 14 volts.

In cities, power cables are generally buried underground. One method used for insulating such cables is shown in Fig. 725. The lower portion of Manhattan Island uses direct current, because the distances are small and the section is very densely populated. Then, too, direct current machines were installed before the use of alternating current became so common. Fig. 726 shows the power plant of the State Line Station, Chicago District Generating Company, located at Hammond, Indiana.

**647. Heat is produced by induction.** Some interesting demonstrations may be performed by the use of alternating currents. A large coil, which is made of coarse, insulated wire, has a heavy iron core. Suppose we connect the terminals of the coil to a 110-volt circuit and then place a hollow copper ring filled with water upon the end of the coil. In a few minutes the water will begin to boil. The currents induced in the copper ring produce the heating effects. We may place a piece of paper on the coil and a metal pan upon the paper. The pan will be heated hot enough to cook an egg in a short time. The demonstration may be varied by placing a beaker of water upon the



*Courtesy of the General Electric Company*

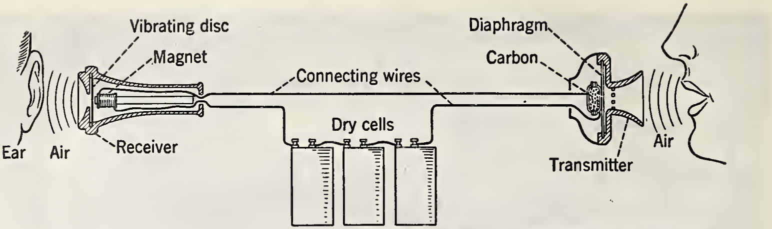
FIG. 726. This power plant has a capacity of 208,000 kilowatts, or more than 277,000 horsepower. Steam turbines are used to drive the generators. The high pressure unit in the foreground develops 76,000 kilowatts, and two of the other units develop 62,000 kilowatts each. Each of the three units is air cooled. The installation is at Hammond, Indiana.

end of the coil. In the beaker we place a small electric bulb whose terminals form a closed circuit with a coil of insulated wire. The filament of the lamp glows, although it is under water and separated from the large coil by the glass beaker. Heating by induction seems almost like black magic.

2/4 1/1000 8/30

## 3. The Telephone

**648. What is the principle of the telephone?** In the induction coil a vibrator is used to vary the strength of a magnetic field. In the transformer, this is accomplished by means of the alternating current. In the simple *telephone* the condensations and rarefactions produced by the human voice act upon a diaphragm which varies the strength of a magnetic field and produces an induced current. (See Fig. 727.) The *simple telephone* is commonly called the telephone receiver. It consists of coils of fine insulated wire wound around the poles of a *permanent* horseshoe magnet, as shown in Fig. 728. A soft iron disc, near the end of such a magnet is thrown into vibration by the sound waves. As this disc vibrates, it changes the direction of the lines of magnetic force, since the iron offers a better path for the lines of force than the air does. Thus the vibrating disc *varies the strength of the lines of force* of the permanent magnet as they cut across the coils of fine wire. A current is in-



*Courtesy of Bell Telephone Laboratories, Inc.*

FIG. 727. Condensations vary the electric current and cause similar sound waves at the receiver end.

duced in the coil by these variations. When current is led into the receiver, it varies the strength of the electromagnet and causes the disc to vibrate.

Let us ground one terminal of the coil of wire and connect the other terminal to a similar coil which is wound upon the magnet of a receiver at the other end of the line and then grounded as shown in Fig. 729. As the sound waves vary the magnetic field, the induced current they set up in the coil causes the same variation in the magnetic field of the receiver at the other end of the line. Its disc will be attracted unequally by the varying current and it will reproduce the same vibrations. The invention of the telephone is generally accredited to Alexander Graham Bell. (See Fig. 730.)

**649. How does the transmitter work?** Since the telephone as described in the preceding section is not suitable for distances beyond a few miles, the modern telephone uses a transmitter which is much more sensitive. It consists of a small box, Fig. 731, filled with particles of granular carbon. The back of the box is a fixed carbon plate attached to one terminal of a battery in series with the primary of a small transformer coil. The front of the box is a plate attached to the vibrating diaphragm, which is connected with the other terminal of the transformer primary. The sides of the box are made of insulating material. When a sound wave condensation presses the carbon particles closer together, their resistance becomes less, and more current flows through the primary coil. This induces a higher voltage current in the secondary. Since the receivers are connected in series with the line wire and the secondary coil, the disc of the receiver is more strongly attracted. When a rarefaction occurs, the pressure on the carbon particles becomes less and a smaller current flows through the primary coil. The variation in the resistance of the carbon particles varies the

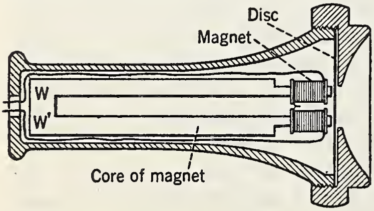


FIG. 728. The telephone receiver.

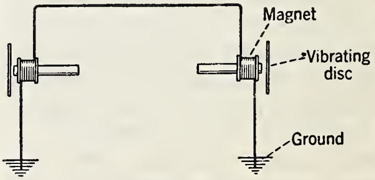
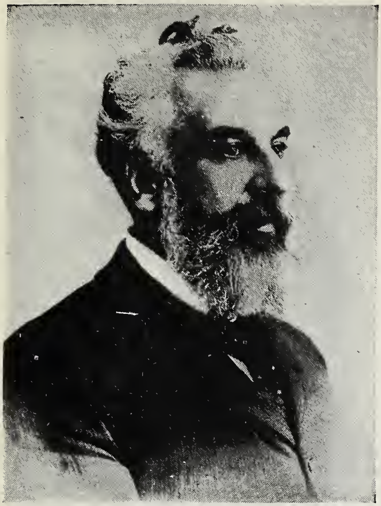


FIG. 729. The simple telephone, commonly called the receiver.



*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 730. Alexander Graham Bell (1847–1922) was an American scientist and inventor. He was much interested in the study of deafness. He is generally considered the inventor of the practical telephone, although his claims to this invention have been disputed. His rights were sustained by the United States Supreme Court.

strength of the primary current and at the same time produces *corresponding* variations in the induced current in the secondary. Thus the receiver disc reproduces the same vibrations as those impressed upon the disc of the transmitter. Fig. 732 shows a local-battery telephone system. Sometimes only one wire is used, the other being grounded as shown by the dotted lines. In the vicinity of trolley lines or electric lighting circuits, two wires must be used to prevent induction from stray earth currents. The use of two wires largely eliminates confusing noises from cross-circuits. On long-distance lines, the current may be too weak to enable us to hear distinctly. Vacuum tubes, called repeaters, Fig. 733, are used to amplify the feeble current. Fig. 734 shows a section of lead cable used for laying telephone wires in conduits. A few years ago, the anchor of a vessel in New York harbor dragged a cable of this type. Try to imagine the difficulty involved in untangling such a network of wires.

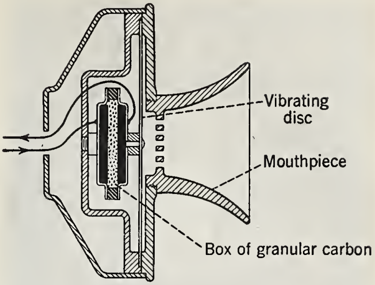


FIG. 731. A simple telephone transmitter diagram.

**650. How is the audiphone constructed?** The invention of permalloy,

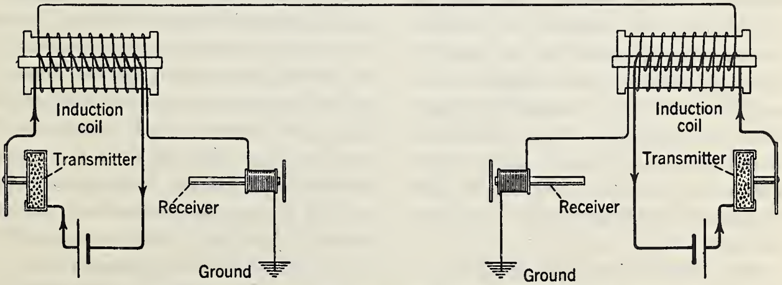


FIG. 732. Diagram to show arrangement of a local telephone system.

*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 733. The vacuum tube is used as a "repeater" tube in long-distance telephone lines.

which contains about 80% nickel and 20% iron, made possible the development of the *audiphone.* A plaster mold is first made to fit the ear of the person whose hearing is impaired. Then a small hard-rubber earpiece is made from the plaster mold. The light, efficient audiphone receiver can then be attached to the earpiece. A carbon microphone, attached to the wearer's pocket, a battery, and a vacuum-tube amplifier make the equipment complete. The audiphone is light and it fits the ear perfectly. A more modern type of apparatus, shown in Fig. 735, utilizes the principle of bone conduction. It is less conspicuous.

★**651. What is self-induction?** Let us connect two dry cells in series and then connect one of the terminals to a piece of wire gauze or to the end of a coarse steel file. When the end of the other wire, connected to the other battery terminal, is drawn along the file or across the gauze, only a few feeble sparks result. When we repeat the experiment after an electro-magnet has been connected in the circuit, the sparks that are produced are much longer and thicker than before. The coils of the magnet produce the same effect as if one had added *extra current.*

*Courtesy of the Bell Telephone Laboratories, Inc.*

FIG. 734. Hundreds of pairs of wires insulated with thin paper are sheathed in lead tubes for use in telephone cables.

Why does an electro-magnet produce such an effect? Since current in a primary coil induces current in a secondary coil surrounding the primary, does it not seem reasonable to suspect that the *current flowing through one loop of coil will induce current in the adjacent loops of the same coil?* Of course, such induction produces an E.M.F. in the adjacent coil, and by Lenz's law such an E.M.F. *opposes* the motion of the current. This type of induction was discovered by an American, Joseph Henry. It is called *self-induction.* (See Fig. 736.)

*Courtesy of the Bell Telephone Laboratories, Inc.*

Fig. 735. The principle of bone conduction is a great aid to those whose hearing is defective.

When the circuit is broken, self-induction *opposes* the "dying out" of the current. It is closely akin to inertia in mechanics. The so-called *extra current added to the inducing current* causes the fattening of the spark when the circuit is broken.

Fig. 736. Joseph Henry (1797–1878) was an American physicist. As Secretary of the Smithsonian Institution, he founded the Weather Bureau. He developed the electromagnet. He is the inventor of the telegraphic principle and of the relay. He is best known for his work in self-induction.

When direct current is used, self-induction occurs only at the "make" and "break" of the circuit. With alternating current, it is always present. Of course it does not occur in *straight* wires, but in *coiled spirals* only.

## 4. Alternating Current Power

★**652. How can we calculate alternating current power?** We know that *self-induction* always occurs in an alternating circuit. Since it opposes the flow of the current, it causes a retarding effect which makes the current in an alternating circuit *lag* behind the E.M.F. Fig. 737 represents both the voltage and amperage curves of an alternating circuit. The current lags behind the voltage and does not reach its maximum so quickly.

Because the current and voltage do not reach their maximum at the same time, alternating current power cannot be found by *multiplying volts times amperes,* as in the case of direct current. We must *multiply volts times amperes times some power factor.* The power factor varies with each individual circuit, but it is always less than *one.* Therefore the *apparent wattage* of an alternating circuit is always more than the *actual wattage.*

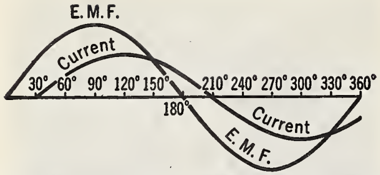


FIG. 737. The current curve lags behind the voltage curve.

**★653. What are reactance and impedance?** Self-induction occurring at each alternation in an alternating-current circuit produces the same effect as a high resistance, but it does not produce the heat effects. In such cases it is called *reactance.* A coil of wire in a *direct current* circuit produces resistance; the same coil connected in an *alternating current circuit* reduces the flow of current by both *resistance* and *reactance.* The combined effect of both factors is called *impedance.* It is not equal to the sum of the two factors, but it is mathematically equal to the *hypotenuse* of a right triangle, of which the reactance and the resistance are sides. (See Fig. 738.) It is possible, in the making of a sensitive telephone receiver, to produce an impedance of several hundred ohms by using small wires to increase resistance and by having many turns to increase reactance. Before Ohm's law can be made to apply to alternating currents, it must be modified to include both *resistance and reactance.* Let us represent the term impedance by the letter *Z;* then we may substitute impedance for resistance in Ohm's law as represented by the following formula:

$$\text{current} = \frac{\text{voltage}}{\text{impedance}}; \quad \text{or,} \quad I = \frac{E}{Z}.$$

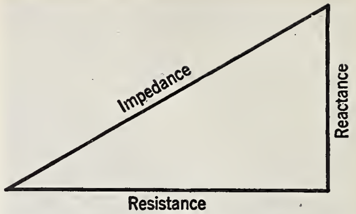


FIG. 738. The relation of impedance to resistance and reactance.

**★654. What is a choke coil?** In order to reduce the current strength in an alternating current circuit, one sometimes introduces a coil of wire of low resistance. It cuts down the flow of current by its high reactance and the heat losses are small. Such a coil is called a "choke coil." Suppose that such a coil has a resistance of only 4 ohms and an impedance of 240 ohms. If it is connected to a 120-volt direct current circuit, 30 amperes of current will flow through the circuit. When it is connected to a 120-volt alternating current circuit, only 0.5 ampere of current will flow through the circuit. Fig. 739 shows how a "choke coil" is connected in a circuit with several lamps. The reactance can be increased decidedly by introducing an iron core into the coil. As the iron core is pushed farther and farther into the coil, the lamps in the circuit grow dimmer and dimmer. Coils of varying reactance are much used in alternating current circuits.

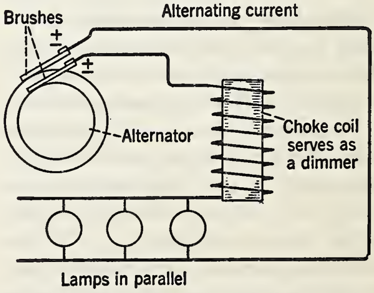


FIG. 739. The choke coil may be used as a dimmer.

## 5. Current Rectifiers

**655. How can one change alternating current to direct current?** In some communities, only alternating current is available. For use in electro-plating or for charging storage batteries, direct current must be used. To change alternating current to direct current, several kinds of *current rectifiers* are used. Engineers sometimes call such devices current transformers. Only a few of them are discussed here.

1. *The motor generator.* This simple device consists of an alternating-current motor and a direct-current dynamo, both mounted on the same shaft. The motor uses alternating current to turn the dynamo, which generates direct current. Storage batteries which are to be charged are connected directly to the dynamo. Thus the alternating current is rectified.

2. *The rotary converter.* The armature of the rotary converter takes current from a high tension alternating current line by means of slip-rings. Such current turns the armature as a motor. A commutator is attached to the other end of the armature. Appliances may draw direct current from the converter by means of the commutator.

3. *Tungar rectifier.* This device finds considerable use for charging storage batteries. It consists of a bulb filled with argon gas at reduced pressure. (See Fig. 740.) The cathode is a coil of tungsten wire, and the anode may be a small cone of graphite or tungsten. The alternating current is so connected with the bulb that the anode and cathode are alternately plus (+) and minus (−). When the anode has a potential several volts higher than the cathode, which is heated by the alternating current from the secondary coils of the transformer, it attracts electrons which are discharged by the hot cathode. These electrons split the argon molecules into positive and negative ions, thus making the argon a conductor. Current flows through the bulb, the resistance, and the battery, which is charged only at those times when the cathode is negative. When the anode is negative, no molecules are ionized, and no current flows. Thus the alternating current is changed into a *pulsating* direct current by the rectifier.

4. *Copper-oxide rectifier.* If one has a plate or disc made of copper with a layer of copper oxide on one side, the electric current will flow from the copper oxide to the copper, but it does not flow easily in the reverse direction. Such a rectifier changes an alternating current into a pulsating direct current. It finds use in radio work.

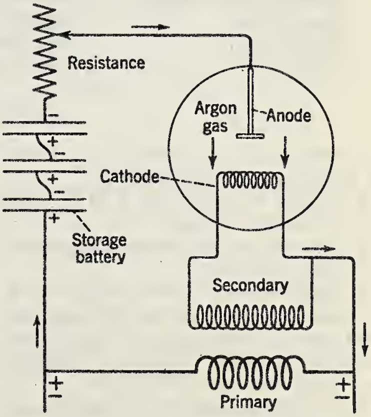


FIG. 740. The tungar rectifier is a device used to rectify alternating current.

5. *The audion tube or bulb.* This device is the heart of a radio set. In addition to the many things that it can do, the audion tube can change alternating current into unidirectional current. Its action is discussed in the following chapter, in which we shall learn of many things that this tube can do.

## Summary

An induced E.M.F. is produced by varying the strength of the magnetic field in which the conductor is placed. The magnetic field may be varied by the use of the "make" and "break"; by an alternating current; or by an iron disc moving in the magnetic field, as with the simple telephone.

The induction coil is used for ignition purposes in gas engines, for medical batteries, and for X-ray work.

The voltage transformer raises or lowers the voltage of an alternating current. A step-up transformer raises the voltage; a step-down transformer lowers the voltage.

Ohm's law does not apply directly to alternating currents, since they are influenced so much by reactance or self-induction.

Alternating currents may be converted into direct currents by motor generators, rotary converters, tungar rectifiers, copper oxide rectifiers, or by audion tubes.

*How many of the following terms can you define or explain? (Arrhenius performed some experiments which indicate that pupils are stimulated when they are in the vicinity of alternating currents surging back and forth through a coil of wire.)*

Induction coil
Secondary coil
Transmission of power
Transmitter
Self-induction
Reactance
Current rectifier
Tungar rectifier
Primary coil
Transformer
Telephone
Power factor
Audiphone
Alternating-current power
Choke coil
Motor generator
Copper-oxide rectifier
Impedance

## QUESTIONS

1. Outline as many methods as you can for producing an induced E.M.F.

2. How does an induced E.M.F. differ from an induced current?

3. Can you see any reasons for using oil in voltage transformers?

4. Eddy currents in the "former" of a galvanometer coil prevent vibrations and bring the coil to rest quickly. Such a galvanometer is called "dead-beat." Explain the action.

5. Why are the coils of a rheostat wound back upon themselves as in Fig. 667?

6. Summarize the advantages of the alternating current. Summarize the advantages of the direct current.

7. From the principle of self-induction explain why a shunt-wound motor will not run on an alternating current, while a series-wound motor will run on either direct current or alternating current.

8. A coil of wire is introduced into an electrical circuit. Will the coil be heated more highly if the current is direct or alternating, provided the voltage is the same? Explain.

9. Why is some type of rectifier necessary for use with a radio set?

# Unit Eleven

# *Radio and Radiations*

## Preview

IN A BURST OF ENTHUSIASM OVER AN IDEA THAT OCCURRED to him, a certain philosopher is said to have remarked: "O God, I am thinking thy thoughts after Thee." If he were permitted to return today to this world of ours, he would soon learn how far behind the Creator he had really been in his thinking. In the realm of the newer physics, he would find men utilizing the X ray to peer through the skin and flesh at the bones beneath. He would see doctors examining the contour of the stomach to learn whether any indications of tumor or cancer are present. He would find men using cosmic ray detectors in an effort to find the sources of such rays.

But what would he think as he watched you tune in on your favorite program and listen to music from Los Angeles, Chicago, Detroit, or New York? It is a modern miracle when one produces an oscillatory electric spark which sends out in all directions a series of waves which may be detected 100 miles distant, 1000 miles away, or which may even encircle the globe. In the field of communication, the world has been reduced to the size of an ordinary living room. We are in almost instant communication with our neighbors, either by the use of wire or wireless.

Mme Curie, who was doing her greatest work about the dawn of the twentieth century, was one of the greatest women who ever lived. She was endowed with unusual acumen and perspicacity. She was an indefatigable worker. Her determination was of the dogged type that sooner or later brings success. When Mme Curie discovered radium and introduced the science of radio-activity she opened up a new field in science. All the large universities of the world took up the study which leads to the structure of the atom itself.

Physicists and chemists were forced to modify their views of matter and energy. Atom-smashing machines are in use in an effort to learn more about the nature of the atom. The transmutation of one atom into another is now an ordinary accomplishment. It is most interesting, too, to learn that the daughter of Mme Curie, who is Mme Joliot, is also a Nobel prize winner. Her special field includes methods of producing radio-active elements artificially.

# *X Rays — Radio — Radio-Activity*

## 1. Cathode Rays

**656. Electrical discharge can take place in vacuums.** Between the knobs of a static machine, it needs a pressure of about 27,000 volts to produce a spark across an air gap 1 cm. in length. If we use pointed terminals for the secondary of an induction coil, it takes about 8000 volts to cause a spark of the same length. Suppose that we have given a glass tube about two feet long with metal terminals sealed in each end. If we connect the tube to the terminals of the secondary of an induction coil, as in Fig. 741, we find that the spark produced when the induction coil is in operation occurs between the points *AB*, and that there is no discharge between the more widely separated terminals *A′B′*. If, however, we pump some of the air out of the tube to produce a partial vacuum, then the discharge occurs between *A′B′*, and the whole tube becomes filled with

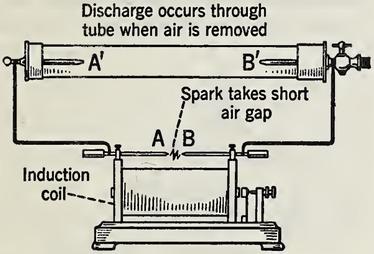
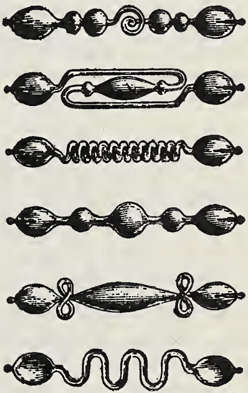

Discharge occurs through tube when air is removed
A′
B′
Spark takes short air gap
A
B
Induction coil

Fig. 741. Electrical discharge through a partial vacuum.



*Courtesy of the Central Scientific Company*

Fig. 742. Geissler tubes.

---

### Vocabulary

Kilo-cycle, 1000 cycles or revolutions per second.

Radio-frequency, having a frequency of more than 10,000 cycles per second; producing waves to which the ear is not sensitive.

Audio-frequency, having a frequency of less than 10,000 cycles per second; producing waves to which the ear is sensitive.

Transmutation, the changing of one element into another.

Acumen, the faculty of discrimination.

Fluorescent, emitting light when exposed to certain rays.

Henry, the unit of electrical inductance.

Farad, the unit of electrical capacity.

Neutron, one of the components of an atom. It carries no electrical charge.

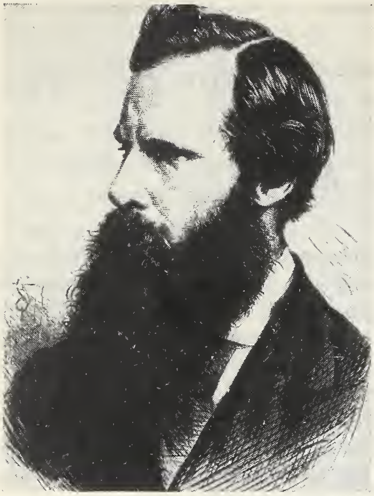


FIG. 743. Sir William Crookes (1832–1919) was an English physicist and chemist. He was an authority on sanitation. He is best known for his work on electrical discharges in vacuum tubes.

bluish-violet light. This experiment proves that the resistance offered to an electrical discharge by a partial vacuum is decidedly less than that of a very much shorter air gap.

The color of the light may be varied by introducing various gases, such as hydrogen, chlorine, nitrogen, neon, etc. The gases in the tube must be under reduced pressure. Very beautiful effects may be produced in a darkened room by using different gases in varicolored glass tubes. Such tubes are known as Geissler tubes. (See Fig. 742.)

**657. What are cathode rays?** It was about the year 1875 that Sir William Crookes discovered what are known as *cathode rays*. (See Fig. 743.) Let us attach a glass tube similar to that shown in Fig. 744 to the terminals of a powerful induction coil. If the air pressure in the tube is reduced to less than 0.001 mm. of mercury, an invisible radiation called the cathode ray is given off from the cathode at nearly right angles. Although we cannot see the cathode rays, yet we can detect their presence in several ways.

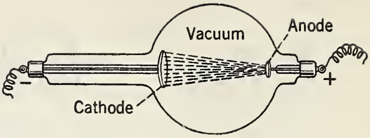


FIG. 744. The cathode-ray tube.

1. *By their heating effects.* If a piece of tungsten is sealed in a tube similar to that shown in Fig. 745, the cathode rays are focused upon it. In a short time the bombardment of the rays upon the tungsten heats it to a white heat.

2. *By their fluorescent effect.* As the cathode rays fall upon the glass tube, they produce a yellowish-green fluorescence. Pieces of zinc sulfide or of colored glass also fluoresce readily when exposed to the cathode rays in an ap-

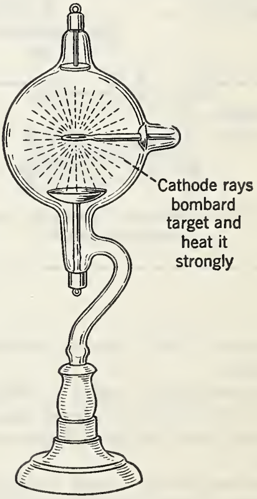


FIG. 745. The cathode rays produce an intense heat effect.

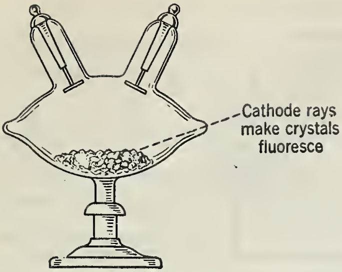


Fig. 746. Certain chemicals fluoresce under the impact of cathode rays.

paratus similar to that shown in Fig. 746.

3. *By the shadow which they produce.* Let us use a tube of the type shown in Fig. 747. A piece of metal is interposed in the path of the cathode rays. The glass flouresces on all sides, but directly behind the metal plate the glass is dark. This proves that the metal plate intercepts the cathode rays.

4. *By their mechanical effects.* Two small glass rods may be mounted horizontally in a cathode ray tube so that they serve as a track along which a light rod with several light vanes attached to it may be made to roll. When the tube is in operation, the cathode rays strike against the vanes in succession and cause it to roll toward the anode end of the tube. (See Fig. 748.)

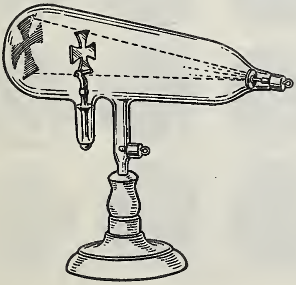
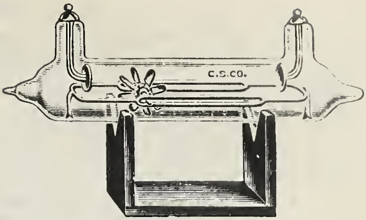


Fig. 747. Metal target intercepts the cathode rays.



Courtesy of the Central Scientific Company

Fig. 748. The cathode rays drive the wheel along the frame as they impinge upon the blades.

**658. What is the nature of cathode rays?** A piece of metal containing a narrow slit may be mounted in a cathode-ray tube at right angles to its length so that a single stream of cathode rays passes through the narrow slit. (See Fig. 749.) If a magnet is held near the tube, the stream of cathode rays is deflected. Such deflection is made visible by the fluorescence of a screen placed at right angles to the slit in the metal plate. It is found that *the cathode rays are tiny negatively charged particles given off from the cathode.* J. J. Thomson called these particles *electrons.* Their mass has been determined. It is found to be about $\frac{1}{1840}$ as great as the mass of the hydrogen atom, which is the lightest atom known. The speed of the cathode particles varies from 20,000 miles per second to over 100,000 miles per second.

**659. What is the Coolidge tube?** About 1926, our newspapers were filled

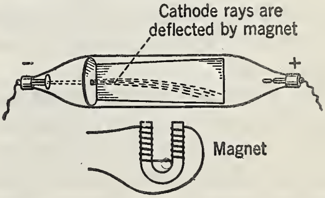


Fig. 749. The cathode rays are attracted by the magnet.

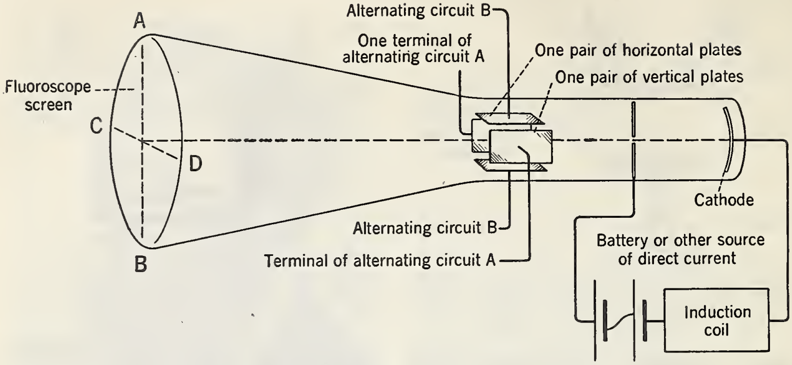
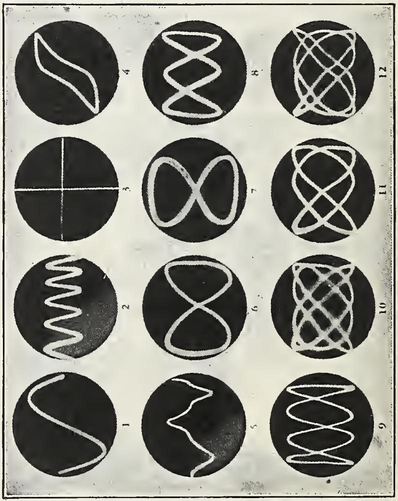

A
Alternating circuit B
One terminal of alternating circuit A
One pair of horizontal plates
One pair of vertical plates
Fluoroscope screen
C
D
Cathode
Alternating circuit B
B
Terminal of alternating circuit A
Battery or other source of direct current
Induction coil

FIG. 750. The oscillograph is used to study various types of currents.

with accounts of the remarkable things that the cathode rays do when they impinge upon different kinds of matter *outside* of the tube. Dr. W. D. Coolidge had constructed a cathode-ray tube, one end of which contained a thin nickel disc through which the cathode rays can pass. By using a voltage of 350,000, he was able to produce as many cathode rays, or beta rays, as 1,000,000 grams of radium bromide can produce. The air in front of the metal disc assumes a purplish glow as its molecules are ionized by the high-speed particles. Germs and spores are destroyed by these cathode rays. Calcite and granite fluoresce, and acetylene gas is changed to a solid powder. A short exposure destroys the hair on a rabbit's ear, and a longer one burns a hole through the ear. The effect of the cathode rays extends only about two feet beyond the metal disc. No practical use seems to have been found for such cathode rays.

**660. What is the oscillograph tube?** The *cathode-ray oscillograph* consists of a high vacuum tube. At one end there is an electrically heated cathode which sends out a stream of electrons. Perforated cylinders used as anodes serve to accelerate the stream of electrons and to focus it so that it will produce a bright spot upon a fluorescent screen at the opposite end of the vacuum tube. (See Fig. 750.) The electron stream passes between two pairs of plates sealed in the tube. The two pairs of plates are set at right angles to each other. If we connect an alternating current to the plates which are


4
8
12
3
7
11
2
6
10
1
5
9

*Courtesy of Chicago Apparatus Company*

FIG. 751. Curves produced by the oscillograph.

above and below the electron stream, it will be bent up and down, thus causing a vertical line on the fluorescent screen. (See Fig. 751.) When an alternating current is applied to the plates on either side of the electron stream, the fluorescent screen shows that the electron stream is bent from side to side. The oscillograph is used to analyze any voltage wave. Complex figures are produced when alternating currents are applied to both pairs of plates. A modification of the cathode-ray oscillograph is coming into use for work in television. It has superseded the scanning disc for such work.

## 2. X Rays

**661. What are X rays?** The X-ray bulb differs little from the Crookes tube, which is used to produce cathode rays. If a tungsten or platinum disc is placed in a cathode bulb in such position that the cathode rays are concentrated upon it, a different type of invisible radiation is produced, Fig. 752. These radiations are called *X rays;* or they are sometimes called, from their discoverer, Roentgen rays. (See Fig. 753.) X rays differ from cathode rays, since they are not affected by a magnet. Unlike light rays, they cannot be reflected or refracted; hence they cannot be focused. It is quite certain that the X rays consist of very short waves set up in the ether by the bombardment of the cathode particles upon the metal disc.

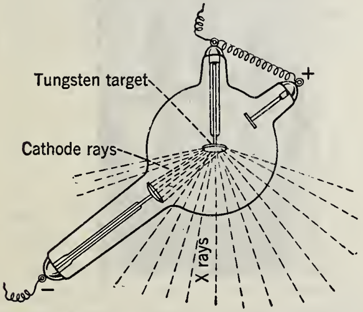


Fig. 752. A simple type of X-ray tube.

*Courtesy of the Eastman Kodak Company*

Fig. 753. William Konrad Roentgen (1845–1923) was a German physicist. He is best known as the discoverer of the X rays or of the Roentgen rays, as they are sometimes called. In 1901 he was awarded the Nobel prize in physics.

**662. What are some uses of X rays?** The most important use of X rays depends upon their ability: (*a*) to affect a photographic plate; (*b*) to penetrate various kinds of matter which is opaque to light, such as wood, flesh, leather, etc. Their penetrating power depends upon the degree to which the bulb producing them is exhausted, and upon

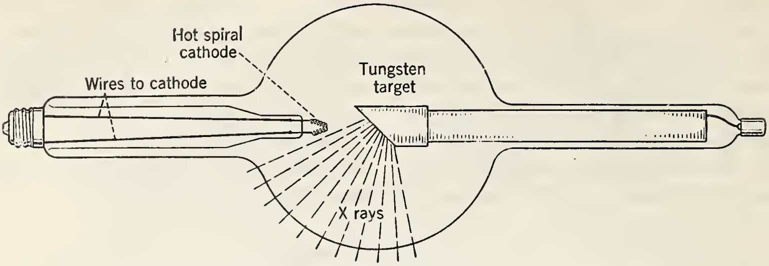
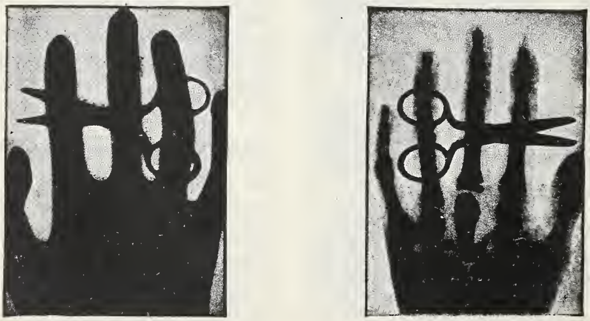


Fig. 754. An X-ray tube of the type devised by W. D. Coolidge.

the voltage used. The rays from a very high vacuum bulb are very penetrating; they are called "hard rays." The less penetrating rays produced by a bulb with lower exhaustion are called "soft rays." The X rays do not penetrate bones and metals as readily as they do wood and fleshy tissues. (See Fig. 755.)

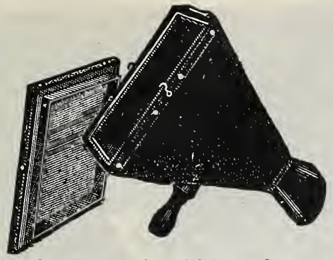
These properties of X rays make them very useful to surgeons in studying bone fractures and in locating foreign substances in the human body. X-ray photographs are taken by placing the object on the cover of the holder in which the plate is enclosed and then bringing the X-ray tube a few inches from it. Such photographs are called *radiographs* or *skiagraphs*. Since the rays are not focused, the picture is only a shadow picture. The bones and metallic objects are darker, because they absorb the X rays more readily. (See Fig. 755.) Before radiographs of the stomach and intestinal tract are taken, the patient is given large doses of buttermilk containing barium sulfate and bismuth subnitrate in suspension. These heavy solids cause the outline shadows of these organs to become very distinct. Cancer on the walls of the stomach shows so clearly that 90% of the diagnoses following X-ray examination prove correct. Dentists use the X ray to determine the position of impacted wisdom teeth and also to ascertain whether teeth are ulcerated.

The X ray is used by a large shoe



*Courtesy of Radium Limited, U.S.A.*

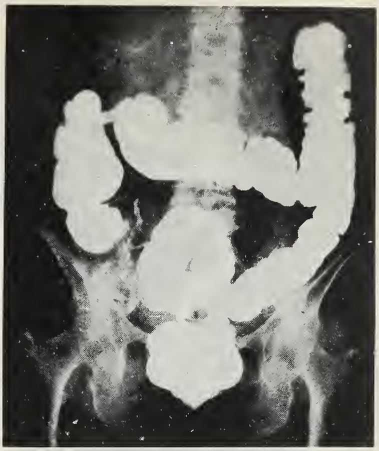
Fig. 755. Radiographs. The cut at the left was made by the action of radium rays. The one at the right by the action of X rays.



*Courtesy of the Central Scientific Company*

FIG. 756. The fluoroscope, which was devised by Edison.

company to test shoes to see if the nailing is properly done. Department stores sometimes use the X ray to aid in fitting shoes, but they do not use it with cheap shoes. Pearls are nearly transparent to X rays, but imitation pearls are decidedly dark by contrast. The X ray has also been used with considerable success in determining whether paintings are the work of the old masters or mere copies. The X ray is now being used in the study of the structure of crystals.



*Courtesy of the Eastman Kodak Company*

FIG. 757. Contour of abdominal organs as seen through the fluoroscope.

**663. What is a fluoroscope?** Thomas A. Edison devised a hood and screen, called a *fluoroscope*, which may be used to show the effects of X rays without photographing them. The sides of the box, Fig. 756, are opaque. The screen is coated with platinum-barium-cyanide, a chemical which Edison found to be exceedingly sensitive to the fluorescent effects of the X rays. If one holds his hand between a fluoroscope screen and an X-ray tube, the bones of the hand may be clearly distinguished. By its use, a doctor can peer into a living body and examine the vital organs. (See Fig. 757.) One woman, for example, was examined for tumor of the stomach. The fluoroscope showed that the obstruction was not on the *walls* of the stomach, but within the stomach itself. Later a large ball of hair was removed from the woman's stomach. A diagnosis is not complete without the X ray.

## 3. Radio

Omit

**664. Who is the inventor?** If one asks this question in the presence of several persons, especially when several nationalities are present, he can easily start an argument. It is not so easy to settle the argument. It matters little, too, concerning which invention the question is asked. If one were to ask, "Who invented radio?" many persons would answer, "Guglielmo Marconi." Few inventions have come as the result of the sudden inspiration of any one

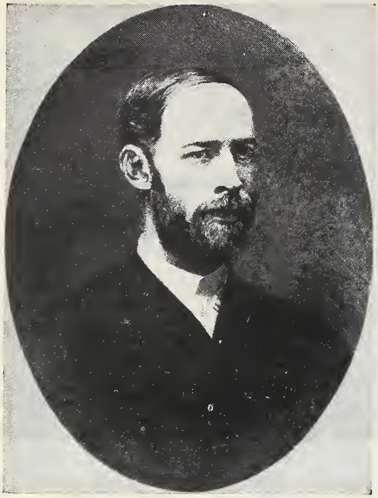


FIG. 758. Heinrich Hertz (1857–1894) was a German physicist. He was the discoverer of the waves which bear his name. He found that waves produced by a static machine can be detected by a loop of wire. He showed that such waves can be reflected, refracted, or even polarized.

FIG. 759. Guglielmo Marconi (1875–1937) was an Italian inventor. He is credited as being the inventor of commercial wireless telegraphy.

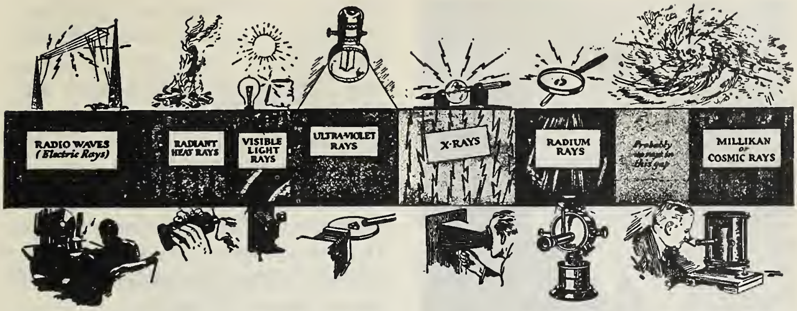
man, but many of them have resulted from the combined efforts of several different workers. Radio is no exception to the general rule.

It was in 1873 that James Clerk-Maxwell published his treatise on *Electricity and Magnetism*, in which he affirmed that electricity and light have the same nature and that both are propagated by means of ether waves in the same manner and at the same speed. Fifteen years later, Heinrich Hertz detected the presence of these electric waves (Hertzian waves) and measured their length. He showed, too, that they can be reflected and refracted just as in the case of light waves. (See Fig. 758.)

Six years later, in 1894, Marconi devised the *coherer* for detecting Hertzian waves. Since he made practical the sending of wireless signals and the method of receiving them, he is generally considered the pioneer and inventor of wireless communication. (See Fig. 759.)

In the study of radio as we know it today, we shall have occasion to mention Edison, who experimented with a three-electrode vacuum tube; to refer to J. J. Thomson, who developed the electron theory which explains many facts; to recall Fleming, who developed a tube similar to the tungar rectifier for changing alternating current to direct current; and to study that development of Lee De Forest, the audion tube. When we consider, too, that others contributed bits here and there to the development of this science, we may conclude that radio is a kind of "League of Nations" invention.

**665. There are different types of ether waves.** Since sound waves are



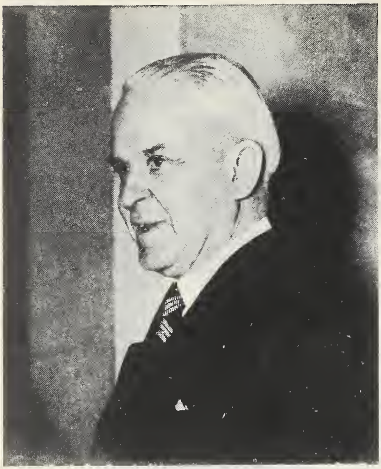
*Courtesy of Popular Science Monthly*

**Fig. 760.** These drawings show the effects which ether waves of different length produce and the manner in which they are produced. The pupil will detect an important gap. Our senses cannot detect any waves here, and no instrument that has been devised can detect them, even if they exist. If you wish to try your imagination, you may write a paper attempting to suggest some of the effects which such missing rays might produce.

not ether waves, but travel through ordinary matter, we do not include them in this list. If we accept the wave theory, then we assume that *light waves and radio waves are ether waves.* Fig. 760 pictures the effect of the so-called ether waves of varying length.

*Radio waves* are long waves, varying in length from a few meters to 10,000 or more meters. *Heat waves* are short ether waves, but *light waves* are even shorter. It would take about 200 light waves laid end to end to equal the thickness of this sheet of paper. Of course, we know the effects produced by heat waves and light waves. If we use a prism to form a solar spectrum and then hold a photographic plate just beyond the violet light waves, the plate will be darkened rapidly. These *ultra-violet rays* are much shorter than the shortest light rays. Some of them may be not more than $\frac{1}{30}$ of the length of those rays which cause the sensation of violet light. They are not visible, but they produce marked chemical effects, such as the darkening of photographic plates, the fading of certain colors, the destroying of bacteria, causing the skin to be tanned, and producing vitamin D.

Surfaces have been polished so smoothly that they do not vary more than *one millionth* of an inch. But such surfaces are rough enough to scatter the very short *X rays.* It is estimated that it would take 300,000,000 of the shortest X rays to make a line one inch long. But still shorter rays are known. Because they were investigated and measured by Robert A. Millikan, they are sometimes called *Millikan rays.* More often they are called *cosmic rays.* It is probable that cosmic rays are not more than $\frac{1}{500}$ as long as the shortest X rays. They are the most penetrating rays known. Different physicists are not in agreement concerning their origin. Dr. Millikan believes they come to the earth from outside, but Dr. Compton and some others consider they may be formed by the disintegration of matter here upon the earth. Cosmic rays were trapped in a lead chamber at the Hayden Planetarium. Their energy was used to turn on the lights in the Trylon of the World's Fair of New York. The



*Science Service*

Fig. 761. Robert Millikan (1868– ) is an American physicist. He was awarded the Nobel prize in physics in 1923. He studied the electron and measured its mass. He is the discoverer of the cosmic rays, which are sometimes known as Millikan rays.

twenty-four lamps in the Trylon gave as much light as a million 100-watt bulbs.

**666. What is the velocity and the frequency of radio waves?** The speed of radio waves is the same as that of light, about 186,000 miles per second, or 300,000,000 meters per second. If we have a generator that is sending out 1,000,000 waves per second, we shall have these waves spread out over 300,000,000 meters by the end of one second. Of course they are 300 meters apart; therefore, the wave length is 300 meters. The same formula,

$$v = nl,$$

that was used for sound waves also applies to radio waves. If we know the *wave length* and the *velocity*, we can calculate the *frequency*. In fact, if any two of the three quantities are known, the third can be found. For example, a station broadcasting on a frequency of 1,000,000 cycles per second is sending out waves that are 300 meters long. (300,000,000 ÷ 1,000,000 = 300.) Since there are 1000 cycles in one *kilocycle*, such a station is broadcasting on a frequency of 1000 *kilocycles*. To produce waves 400 meters long, a station must send out 750 kilocycles per second. The wave lengths that are to be used by each station are assigned by the Federal Radio Commission.

**667. What do we need for radio work?** In our study of sound, we learned that it is necessary to have some *vibrating body to produce the sound waves, some medium to transmit them*, and *the ear to serve as a receiver.* Similarly, in radio work, some apparatus is needed to produce radio waves; we assume that the ether transmits them; and, we must have some device to detect them. They travel all around us, but we are not conscious of their presence, since we cannot see them, feel them, or detect them by any one of our senses.

**668. How can radio waves be generated?** Many methods have been used to produce radio waves. For example, the electric spark from a static machine or from an induction coil oscillates rapidly and sends out radio waves. The damped waves which it produces, Fig. 762, are suitable for sending out signals, but they cannot be used for broadcasting the human voice or music. A *continuous carrier wave* must be used for the latter purpose. (See Fig. 764.)

If we refer to Fig. 763, we can see how damped wave signals can be transmitted. When the contact key is

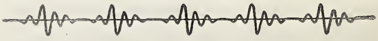


Fig. 762. Damped waves.

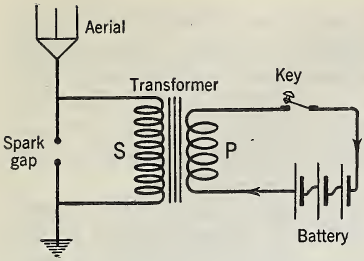

Aerial
Transformer
Key
Spark gap
S
P
Battery

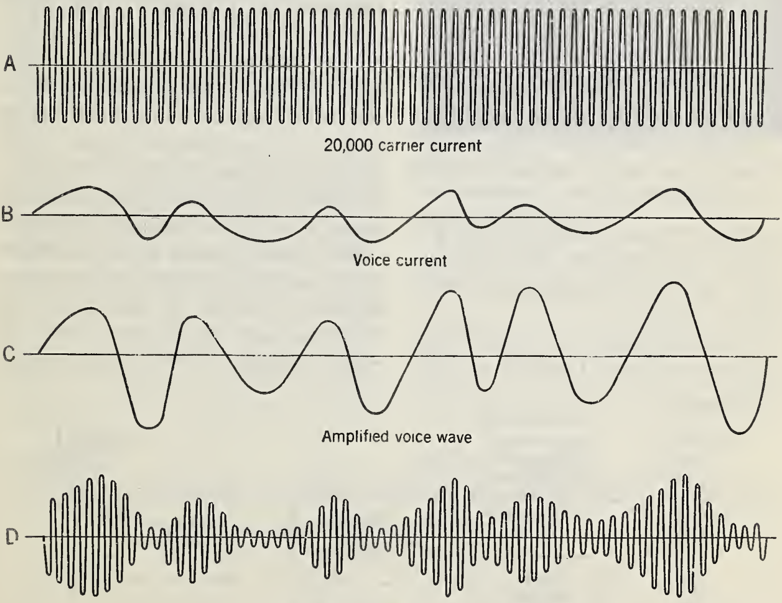
FIG. 763. Simple system for transmitting wireless signals.

pressed, it closes the battery circuit through the primary of a spark coil. An E.M.F. of high voltage is induced in the secondary, and a spark leaps across the spark gap. One terminal of the spark gap is grounded, and the other is connected to the antenna or aërial. A short train of waves thus produced corresponds to a "dot" in the radio code and a longer train to a "dash."

At one time, the continuous carrier wave used for wireless telephony was produced by means of a special arc, or by the use of an Alexanderson generator, whose rotor made thousands of revolutions per minute. Now the marvelous *audion tube,* which can do almost anything, is used as a generator of oscillations. The frequency of its oscillations is controlled by the use of induction coils and condensers which may vary inductance and capacity.

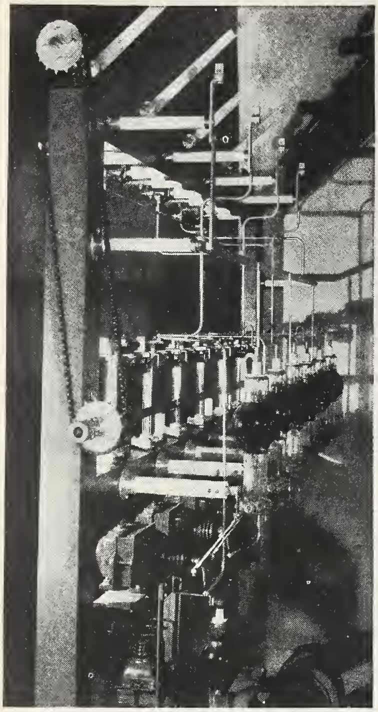
**669. How is the voice put on the air?** The audion tube, which will be more fully described later, serves three purposes in radio transmission.

1. Such a tube is used as an *oscillator* to produce high-frequency waves that serve as undamped carrier waves. (See


A
20,000 carrier current
B
Voice current
C
Amplified voice wave
D
Carrier modulated by voice current

*After Bell Telephone Laboratories*

FIG. 764. *A.* 20,000-cycle carrier current. *B.* Voice current wave. *C.* Amplified voice wave. *D.* Carrier wave modulated by voice wave.



*Courtesy of the Bell Telephone Laboratories, Inc.*

Fig. 765. Water cooler. 50-kilowatt experimental tube used as an amplifier.

Fig. 764*A*.) Because their frequency is so high that they do not affect the human ear, they are known as *radio-frequency waves.*

2. A second audion tube serves as a *modulator*. It serves to blend or unite the *voice wave,* which is capable of affecting the auditory nerve, with the carrier wave. The voice waves, which are represented in Figs. 764*B* and 764*C*, are known as *audio-frequency waves*. Fig. 764*D* represents one form of *modulated wave.*

3. A bank of audion tubes is used to *amplify* the modulated wave before it goes on the air. Sometimes the voice wave is amplified before it is modulated. (See Fig. 764*C*.) These audion tubes are similar to the ones used in receiving sets, but they are much larger. Some have an output of 50 kilowatts, or nearly 70 horsepower. (See Fig. 765.)

The diagram of Fig. 766 shows how audion tubes are used to put the voice on the air. When one talks or sings, condensations and rarefactions of the air are produced. These air waves cause variations in the primary circuit of the telephone transmitter or the microphone. Corresponding E.M.F.'s are thus induced in the secondary, which causes changes in the potential of the grid of the modulator vacuum tube. After the modulated wave has been amplified, it goes through an oscillation transformer to the transmitting aërial.

**670. How are radio waves received?** It is a long step from the coherer which Marconi invented, or the crystal set that was used in the early years of radio reception, to the modern audion

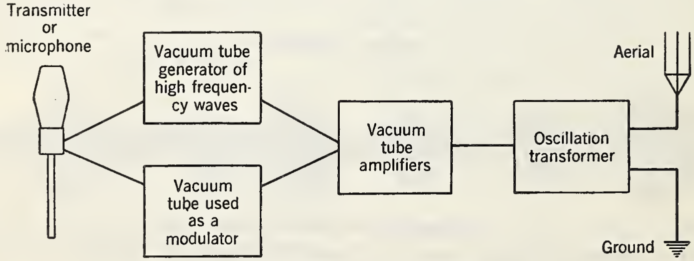


Fig. 766. Diagram to show how the voice is put on the air.

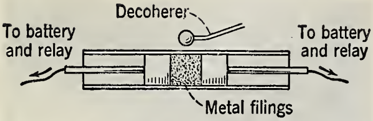


FIG. 767. A type of coherer as used by Marconi to detect wireless signals.

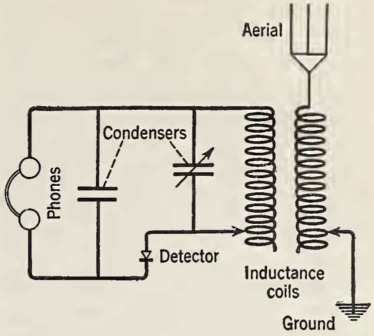


FIG. 770. A diagram of an old crystal-set type of receiver.

tube which now serves as detector and amplifier in receiving sets. The coherer is now of historic interest only.

1. *The coherer.* This simple form of detector was made from a tube which contained a mixture of metal filings. (See Fig. 767.) Two metal plugs made contact with the filings, and they were connected in series with a battery and a relay, which acted as a circuit closer for a telegraph sounder. Normally, the filings offered so much resistance that the battery current was too feeble to operate the relay. When the Hertzian waves came into contact with the iron filings, they caused them to cohere. Their resistance was reduced and enough current flowed through them to operate the relay and produce the signal.

2. *Crystal detectors.* Like the coherer the crystal detector has historical importance, but it is still used in certain applications. Galena, an ore of lead, was one of the best crystals used Such a crystal permits current to flow through it readily in one direction, but checks its flow in the opposite direction. Fig. 768 shows how a crystal detector changes an alternating-current modulated wave into a *pulsating,* direct-current wave. These pulsations are combined in groups by the receiver to form waves of lower frequency. (See Fig. 769.) Thus the incoming radio-frequency waves, which had such a high frequency that the diaphragm of the earphones could not respond to them, were changed into audio-frequency waves. Fig. 770 shows how the crystal can be connected with a pair of earphones and the variable inductance coils which can be tuned by the use of the fixed and variable condensers connected in the circuit.

3. *The audion tube.* Such a tube is the heart of the transmitting station. It is just as important in the modern receiving set. Its development is interesting. A few years after Edison invented the incandescent lamp he began experimenting with a vacuum tube like

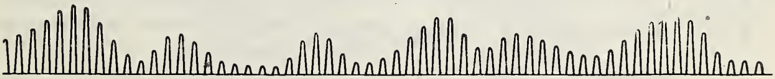


FIG. 768. Pulsating direct-current wave.

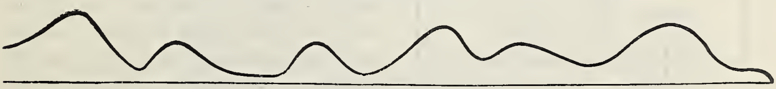


FIG. 769. How the receiver produces audio-frequency waves from the waves of Fig. 768.

that shown in Fig. 771. He found that current would flow through the galvanometer when the filament was heated by the battery, provided the positive side of the battery was connected to the plate. No current flows when the negative side of the plate is joined to the battery. No one could explain in those days how the current got from the hot filament to the plate, because the electron theory had not been developed. This experiment, which was known as the *Edison effect*, was soon forgotten. Now that J. J. Thomson has given us the electron theory, we know that electrons are expelled from the hot filament, or "boiled out" of it. The positively charged metal plate attracts the electrons. (See Fig. 772.)

More than twenty years later, Fleming began to use a similar bulb to charge storage batteries, since it can change alternating current into a unidirectional current. The amount of current flowing through such a bulb may be increased in two ways.

1. If we reduce the resistance in the filament circuit, more current flows through the filament, and its temperature is increased. More electrons are pushed out of the filament when its temperature is increased.

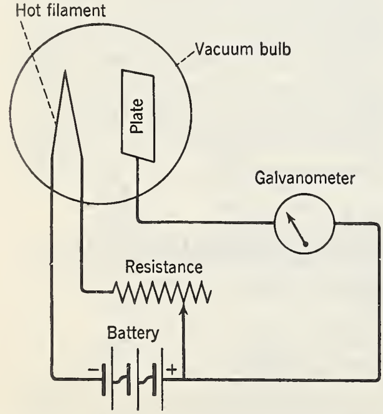
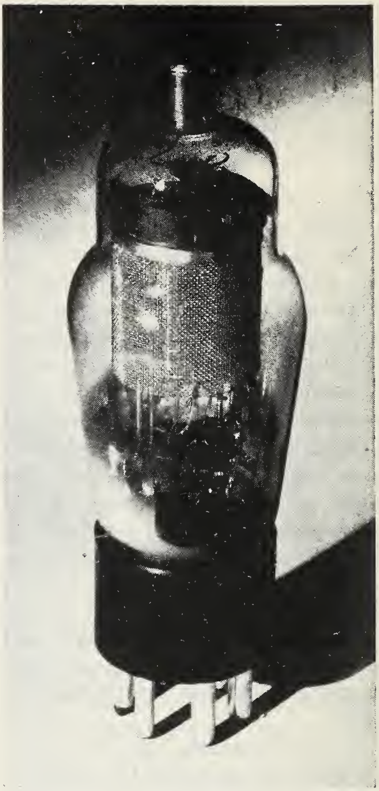


Fig. 771. Diagram to show the Edison effect.



*Courtesy of the Bell Telephone Laboratories, Inc.*

Fig. 772. Amplifier tube as used for receiving.

2. If we increase the positive voltage on the plate, it attracts electrons more strongly. The device used in this manner for charging storage batteries was called a *Fleming valve.* (See Fig. 773.)

It was the work of Lee De Forest that made the audion tube the modern miracle that it is today. J. J. Thomson's electron theory explains that the electrons which are emitted by the filament are attracted to the plate. Thus the problem of the Edison effect is

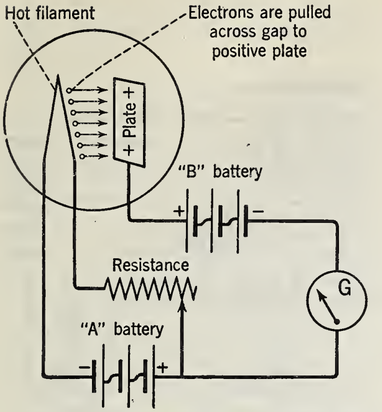

Hot filament
Electrons are pulled across gap to positive plate
+ Plate +
"B" battery
+
−
Resistance
G
"A" battery
−
+

FIG. 773. The positive charge on the plate "pulls" electrons.

solved, but De Forest invented a device to control the flow of electrons. He introduced an extra electrode, called a *grid*, between the filament and the plate. Let us refer to Fig. 774 to see what the grid really does. The plate is kept *positively* charged. Electrons are "boiled out" of the hot filament. The grid acts as a valve between the two to control the flow of electrons. It is similar to a traffic policeman at the entrance to a one-way street. When his gesture is positive, the traffic moves; it halts when his gesture is negative. When the grid is *positively* charged, it helps to attract or "pull" the oncoming electrons. When it is *negatively* charged, it repels or "pushes" the electrons so that few or none of them reach the plate. Even a *feeble* alternating current applied to the grid can control a powerful current in the plate circuit. The alternating current charges the grid positively and then negatively. Only the upper half of a modulated wave of the type shown in Fig. 764 can pass the grid of this vacuum valve which is known as the *audion tube.*

**671. How is a standard receiving set constructed?** The battery set is coming into use again, and we shall refer to such a set, because it is much easier for the beginner to understand what each part of a receiving set is intended to accomplish. (See Fig. 775.)

1. *The filament circuit.* In this circuit, an "A" battery is used to heat the filament. The amount of current flowing through the filament is controlled by the resistor, *R*. As we decrease the resistance in the circuit, more current flows through the filament, and more electrons are emitted.

2. *The plate circuit.* In this circuit, the positive terminal of a "B" battery is connected to the plate of the audion

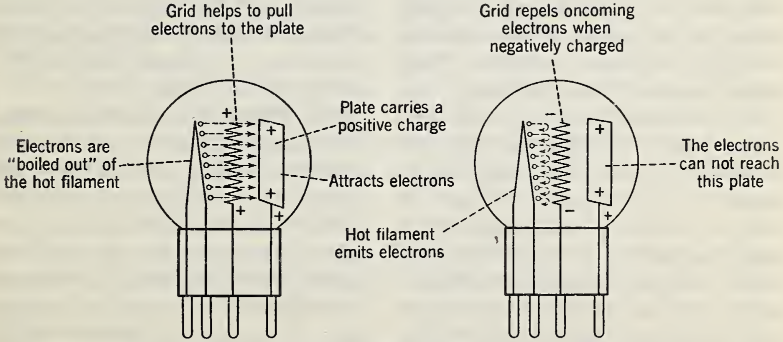

Grid helps to pull electrons to the plate
Electrons are "boiled out" of the hot filament
Plate carries a positive charge
Attracts electrons
Hot filament emits electrons
Grid repels oncoming electrons when negatively charged
The electrons can not reach this plate
+
−

FIG. 774. How the grid controls the current in the plate circuit.

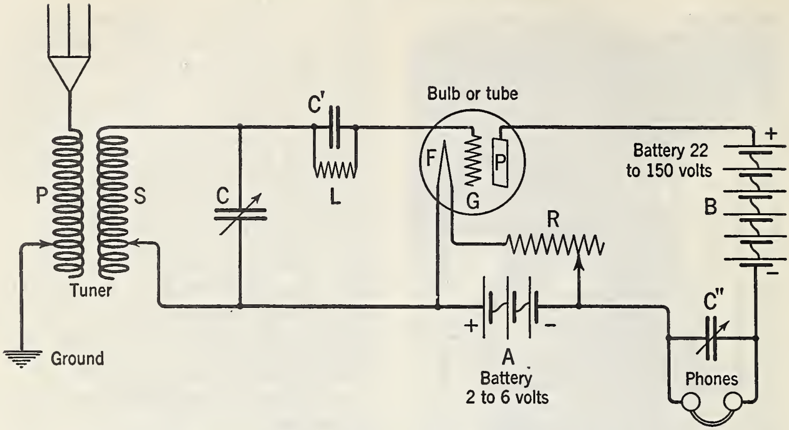


FIG. 775. Diagram to show the parts of a standard receiving set.

tube. Thus it keeps the *plate charged positively at all times.* The other terminal of the circuit is connected in series with a set of earphones or a loud speaker to one terminal of the "A" battery. The plate circuit includes the plate, the "B" battery, the loud speaker, and the filament with its stream of electrons flowing to the plate. We can increase the magnitude of this stream of electrons by increasing the temperature of the filament, or by raising the voltage of the plate.

3. *The grid circuit.* As radio waves come from a broadcasting station, they induce in the aërial of the receiving set high-frequency currents. These radio-frequency currents induce currents of the same frequency in the *grid circuit,* which includes the grid, the secondary of the tuner, and a condenser. In this manner, the grid is charged positively and negatively in rapid succession. By its action as a valve, the grid changes the *radio-frequency alternating* currents into *pulsating* currents that flow in one direction only. (See Fig. 769.) The pulsating wave which thus reaches the plate circuit causes the diaphragm of the loud speaker to vibrate and produce condensations and rarefactions of the same nature as those impressed upon the microphone of the broadcasting station. From the diagram one notices that the grid circuit is connected with the antenna-ground system inductively so that it is always influenced by the radio-frequency waves induced in the antenna system. A grid leak, *L,* is connected across the terminals of the condenser of the grid circuit. It has a high resistance, rated in *megohms,* or millions of ohms. It permits electrons that may accumulate on the grid and interfere with its action to leak away.

**672. What is the principle of tuning?** In the study of sound, we found that a vibrating tuning fork can throw into vibration by sympathetic vibration another fork some distance away, provided both forks have the same frequency. Each *succeeding* condensation from the first fork continues to impinge upon the second fork until it finally causes it to vibrate. The principle of tuning in radio is similar to sympathetic vibrations or resonance by sound waves.

When a high-frequency Hertzian wave strikes your antenna, it induces current in your receiving set. If the induced wave makes the circuit through your receiving set and back to the antenna by the time the next wave arrives, each succeeding wave helps to build up the current flowing through the set. If the wave makes the circuit through your set either more slowly or more quickly than the appearance of the next wave, interference results, and the waves tend to nullify one another.

*Condensers and inductance coils* are used in tuning receiving sets. In the tuner of Fig. 775 it is possible to vary the *inductance* by means of a sliding conductor which may make contact with any one of the various loops of the tuning coil as indicated by the arrow. The larger the number of loops, the greater the self-induction. One can also vary the inductance by increasing the distance between the primary and secondary coils. Increasing the inductance in the circuit of a set increases the wave length to which the set is attuned. The antenna has a natural wave length to which it responds. Such wave length depends upon the length of the antenna, but it may be changed by the use of inductance coils.

★The *henry is the unit of inductance.* A circuit has an inductance of one henry when an inducing current which varies at the rate of one ampere per second causes an induced pressure of one volt. The *milli-henry*, or the *milhenry*, is more commonly used in wireless work. The milhenry is one-thousandth of a henry, but it is equal to 1000 *micro-henrys.*

Both *fixed and variable condensers* are used in radio reception. (See Section 538.) The *capacity* of a condenser is measured in *farads.* A condenser has a capacity of one farad if it gives a pressure of one volt when charged with one *coulomb* of electricity. The unit of electrical quantity is the coulomb, which is equal to the amount of electricity, or the number of electrons, transferred by a current of one ampere flowing for one second. Because the farad is such an extremely large unit, the *microfarad*, which is one-millionth of a farad, is used as a capacity unit in radio work. Increasing the capacity of the condenser increases the wave length to which a radio set responds.

**673. Additional vacuum tubes produce amplification.** At broadcasting stations, the *triode* vacuum tube is used as a *generator* of radio waves, as an *amplifier* of such waves, or as a *modulator* of radio waves. In receiving sets, such tubes are used as *detectors* of Hertzian waves, or as *amplifiers* of them. When used as amplifiers, vacuum tubes may be connected in the radio-frequency circuit to amplify the waves before they enter the detector tube, or they may be connected in the audio-frequency circuit to amplify the waves as they come from the detector. Fig. 776 shows the diagrammatic scheme for amplification. From the aërial the radio-frequency waves go to the tuner. Then they pass through one or more audion tubes for amplification. Next they pass to the detector which changes the radio-frequency waves into pulsating audio-frequency waves. Then one or more audion tubes may be used to amplify the audio-frequency waves before they reach the loud speaker. Thus the volume of the sound is intensified.

To secure *amplification of the radio-frequency waves*, the plate circuit of the

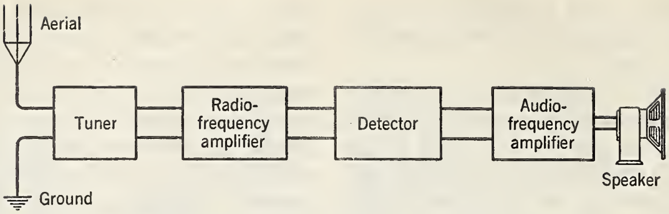

Aerial
Tuner
Radio-frequency amplifier
Detector
Audio-frequency amplifier
Speaker
Ground

FIG. 776. Diagram to show how incoming waves are amplified.

first audion tube does not contain the loud speaker, but it is connected to the *primary* of a transformer. The *secondary* of this transformer is connected with the grid of the detector tube. (See Fig. 777.) The transformer steps up the voltage in the secondary, and the current is strengthened so that the detector tube responds to more feeble waves from more distant stations. One, two, or more tubes may be used in this manner to produce different stages of amplification. A variable condenser is used with the transformer in the amplifying circuit to permit the tuning of this circuit.

The *audio-frequency waves may also be amplified* as they come from the plate circuit of the detector. Here again the plate is connected in series with the primary coil of a transformer. The secondary of the transformer, which is connected to the grid of the next tube, steps up the voltage in the circuit. We have already seen how the grid controls the amount of current in the plate circuit. As the voltage on the grid is increased, it will pull more electrons from the filament when it carries a plus charge, and repel more strongly when it is negatively charged. Thus more current will flow in the plate circuit of the amplifying tube. One or more *stages* of audio-frequency amplification may be used. Some modern receiving sets have several stages.

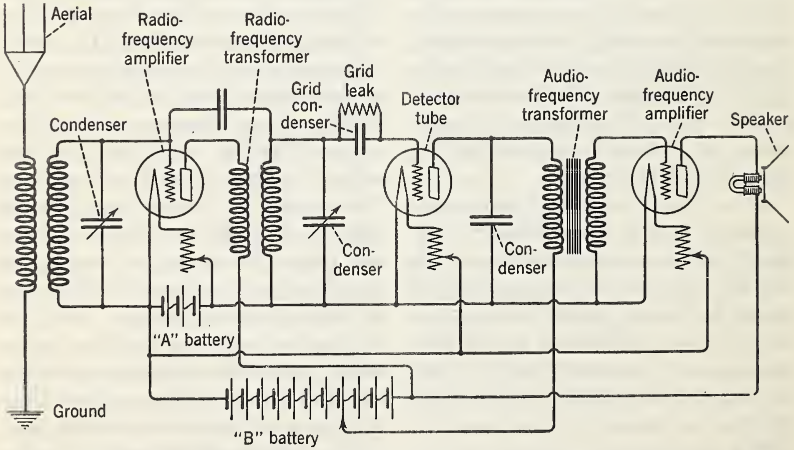

Aerial
Radio-frequency amplifier
Radio-frequency transformer
Grid condenser
Grid leak
Detector tube
Audio-frequency transformer
Audio-frequency amplifier
Speaker
Condenser
Condenser
Condenser
"A" battery
Ground
"B" battery

FIG. 777. One stage of radio-frequency amplification and one stage of audio-frequency amplification.

**674. Alternating current is used in receiving sets.** The radio sets now sold give excellent results when connected to a lighting circuit supplying from 110 to 125 volts. Some type of rectifier is used to furnish direct current for the audion tubes, the plate circuits, and for the magnet of the dynamic loud speaker. Transformers are used to reduce the voltage to the value required. For the tubes, it is usually reduced from 110 volts to about 2 volts. To prevent the humming noise produced by the alternating current, tubes with special filaments are used, or the filament may be surrounded by a cylinder which emits electrons as it is heated by the filament. A filter is used to prevent the flow of current which has too high or too low a frequency.

**675. What is wired radio?** By the use of high-frequency carrier waves, it is now possible to send at the same time several waves of different frequency over a single pair of wires. Telegraph messages may be sent in this manner, and at the same time several different conversations may be transmitted as modulated voice waves. Just as our radio receiving set can be tuned to receive different wave lengths, so it is possible to tune in to receive any desired wave that is being transmitted over the wires. Power lines, too, may be used commercially for transmission of *wired radio.*

**676. How does the radio compass work?** An aërial wire stretched above the ground forms with the earth a condenser whose capacity varies with the length of the wire. The radio listener soon learns that his aërial is more responsive to waves coming from a particular direction. A *loop* antenna is made by winding one or more turns of wire on a frame from one to four feet in diameter. This frame is mounted in a vertical plane and rotated about its vertical axis. When such a loop antenna is connected in a properly tuned circuit and turned so that one edge points toward a transmitting station, the reception will be at a minimum. When the loop is turned broadside toward the station, there will be a maximum of reception. Such a loop forms the basis of the *radio compass.*

Radio compasses are maintained along the coast by the United States Navy Department to help ships in a storm to locate their position. A message from the ship may be picked up by three or four of these stations, for example, and from the positions of the stations and the distances between them, the location of the ship can be calculated, and its position broadcast. The ship may carry a radio compass and determine its position from the directions of radio-beacon stations installed in lighthouses along the coast. An aviator flying in a fog or over a large body of water uses a radio compass to guide his plane in the right route. (See Fig. 778.)

**677. How is the microphone constructed?** The *granular carbon* type of transmitter does not differ greatly from the telephone transmitter. It consists of a diaphragm clamped in a metal frame between two variable resistance elements.

The *condenser* microphone, now largely used, consists of two plates separated by an air gap of about 0.001 in. in thickness. One of these plates is a flexible diaphragm which is thrown into vibration by the sound waves that impinge upon it. Thus the air space between the plates is lessened or increased and the capacity of the condenser varies. Such vibrations cause a fluctuation of the current flowing in

*Courtesy of General Electric Company*

FIG. 778. Admiral Richard E. Byrd with the all-wave radio set he used during his Antarctic explorations.

the battery circuit with which the condenser plates are connected. In this manner, sound waves are converted into electric current, which is amplified in a vacuum tube.

**678. What is the structure of the loud-speaker?** The *electro-dynamic loud-speaker* is now in common use. In the older types of speakers, a permanent magnet was used, but in the newer electro-dynamic speaker, a powerful electro-magnet is energized by current from a rectifier. The electro-magnet has an iron core and it is encased in an iron cylinder. (See Fig. 779.) The moving element is a small coil of a few turns of wire, which is placed over the core, but separated from the core and the iron frame by an air gap. The core receives its current from a low-voltage transformer connected to the receiving set. This light coil is rigidly attached to the edge of a cone-shaped diaphragm. As the coil vibrates in response to the fluctuating current from the output side of the receiving set, the diaphragm, which is mounted on flexible supports, reproduces the sound waves with little or no distortion.

**679. Newer types of audion tubes have been developed.** Some audion tubes used for reception are *all-metal tubes*. A special glass is used to insulate the lead-in wires. Such tubes are of smaller size, and they furnish better protection against the influence of electrostatic disturbances from outside the tube.

The *screen-grid tube* differs from the ordinary three-electrode tube in only one important respect. The extra grid consists of a metal screen which is placed between the plate and the ordinary grid of the three-electrode tube. Since it is positively charged with respect to the filament, it serves as an electrostatic screen between the two electrodes and permits the tube to work better in amplifying radio-frequencies.

The *pentode tube* has yet another grid between the screen grid and the plate. The extra grid tends to suppress any electrons which might have a tendency to flow from the plate to the screen

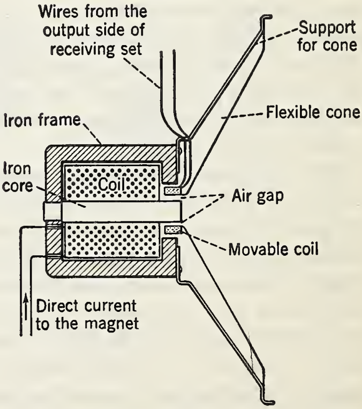
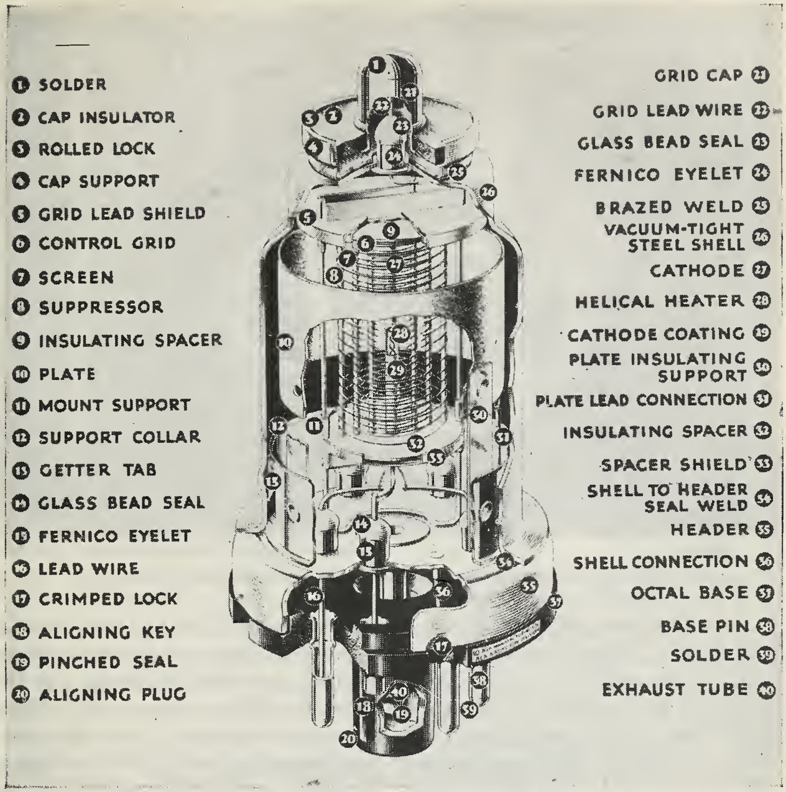

Wires from the output side of receiving set
Support for cone
Flexible cone
Iron frame
Iron core
Coil
Air gap
Movable coil
Direct current to the magnet

FIG. 779. Electro-dynamic loud speaker.

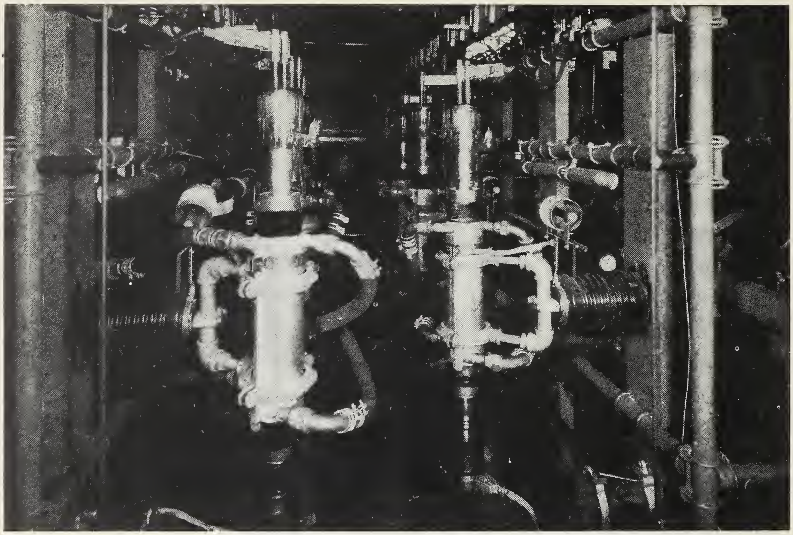

① SOLDER
② CAP INSULATOR
③ ROLLED LOCK
④ CAP SUPPORT
⑤ GRID LEAD SHIELD
⑥ CONTROL GRID
⑦ SCREEN
⑧ SUPPRESSOR
⑨ INSULATING SPACER
⑩ PLATE
⑪ MOUNT SUPPORT
⑫ SUPPORT COLLAR
⑬ GETTER TAB
⑭ GLASS BEAD SEAL
⑮ FERNICO EYELET
⑯ LEAD WIRE
⑰ CRIMPED LOCK
⑱ ALIGNING KEY
⑲ PINCHED SEAL
⑳ ALIGNING PLUG
GRID CAP ㉑
GRID LEAD WIRE ㉒
GLASS BEAD SEAL ㉓
FERNICO EYELET ㉔
BRAZED WELD ㉕
VACUUM-TIGHT STEEL SHELL ㉖
CATHODE ㉗
HELICAL HEATER ㉘
CATHODE COATING ㉙
PLATE INSULATING SUPPORT ㉚
PLATE LEAD CONNECTION ㉛
INSULATING SPACER ㉜
SPACER SHIELD ㉝
SHELL TO HEADER SEAL WELD ㉞
HEADER ㉟
SHELL CONNECTION ㊱
OCTAL BASE ㊲
BASE PIN ㊳
SOLDER ㊴
EXHAUST TUBE ㊵

*Courtesy of the R.C.A. Manufacturing Company*

Fig. 780. One of the later types of radio tubes.

grid. It finds use as an audio-frequency amplifier. From Fig. 780 the pupil may get an idea of the large number of different types of tubes which have been developed for special purposes in radio, for oscillators, amplifiers, or for reception.

**680. The radio telephone speaks across the Atlantic Ocean.** Since January 7, 1927, it has been possible to converse between New York and London. You do not drop a nickel in the slot, but you pay $21 for a 3-minute conversation with your friend in London, unless you are willing to wait for a night rate of $15. Part of the service is over the land telephone and part by wireless. From your own phone your voice goes to the Central Station of the American Telephone and Telegraph Company in New York. Then it travels by wire to Rocky Point, Long Island. Here it is amplified by twenty-three vacuum tubes, each about two feet long. It is amplified 2,000,000,000 times and sent across the Atlantic Ocean on a wave length of 5000 meters. (See Fig. 781.) One writer says, "The 70-horsepower voice with which we shout electrically across the ocean has



*Courtesy of the Bell Telephone Laboratories, Inc.*

Fig. 781. Bank of water-cooled amplifiers used for trans-Atlantic telephony.

the collective speaking power of about 2,000,000,000 people, nearly the population of the earth." But when your voice reaches Wroughton, England, it is 1000 times fainter than it was when it left your phone. "Our 70-horsepower voice has dwindled to something inconceivably fainter than the inaudible whisper of a dying man." At Wroughton it is again amplified and sent 70 miles to London, where the London operator connects you with your party. Fig. 782 shows the different stages used in trans-Atlantic telephony. Your reply from London comes back by wire to Rugby, England, where it is amplified as before, and sent to New York by way of Houlton, Maine.

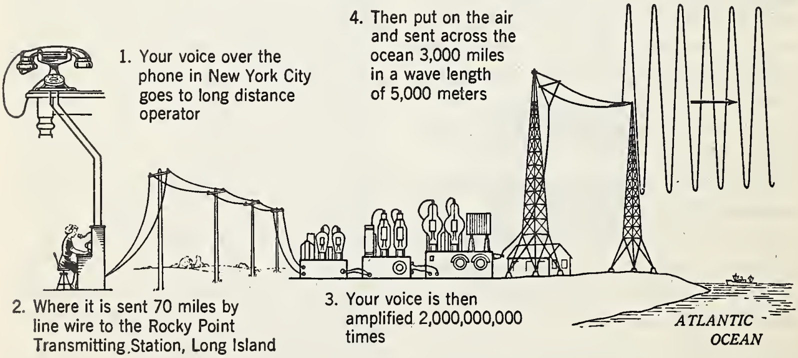

1. Your voice over the phone in New York City goes to long distance operator
2. Where it is sent 70 miles by line wire to the Rocky Point Transmitting Station, Long Island
3. Your voice is then amplified 2,000,000,000 times
4. Then put on the air and sent across the ocean 3,000 miles in a wave length of 5,000 meters
ATLANTIC OCEAN

Fig. 782. Diagram to show how one in

**681. The photo-electric cell has many uses.** This cell consists of a vacuum tube, a part of whose inside surface is coated with some metal, such as potassium or caesium, which is sensitive to light. The negative lead-in wire of the cell is connected to this photo-electrically active metal coating. The anode consists of a ring of inactive metal, such as nickel or platinum, mounted in the center of the vacuum tube. If we connect such a photo-electric cell in circuit with a battery and a galvanometer, we find that the current flowing through the galvanometer varies with the intensity of the light shining on the sensitive coating of the tube. The number of electrons emitted by the metal coating is directly proportional to the intensity of the light which shines upon it.

The photo-electric cell is sometimes called "the electric eye." It is used in many different ways. Because it can cause an electric current to fluctuate, it finds use in opening hotel doors and garage doors automatically. It is used to count the number of automobiles that pass through the Holland Tunnel. It can be used to operate a burglar alarm system that sounds an alarm when a burglar's flashlight shines upon a safe door. It can be used to measure the intensity of light in foot-candles. In addition to numerous other uses, the photo-electric cell finds use in television. (See Fig. 783.)

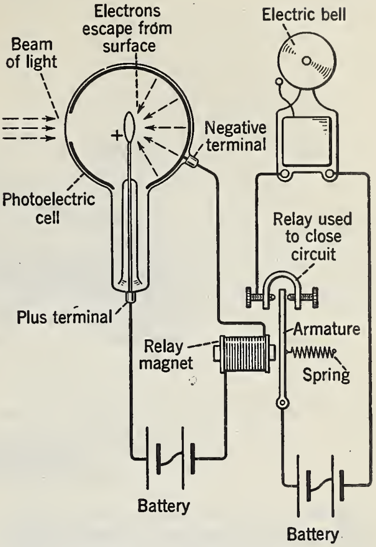
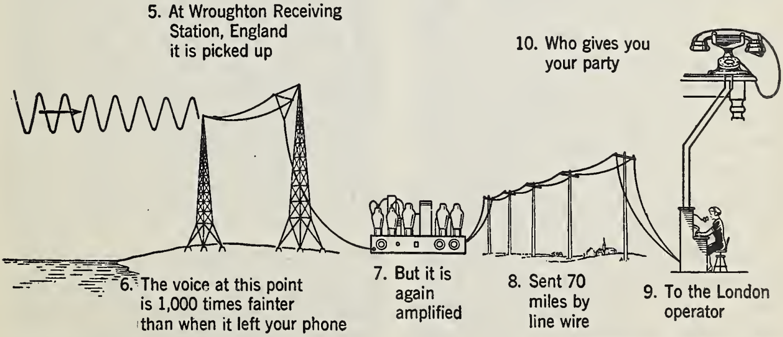

Electrons escape from surface
Electric bell
Beam of light
+
Negative terminal
Photoelectric cell
Relay used to close circuit
Plus terminal
Armature
Relay magnet
Spring
Battery
Battery

FIG. 783. The photo-electric cell may be used to control a burglar alarm.

**682. Television is here.** For *television*, which comes from the Greek word meaning "distant" and the Latin


5. At Wroughton Receiving Station, England it is picked up
10. Who gives you your party
6. The voice at this point is 1,000 times fainter than when it left your phone
7. But it is again amplified
8. Sent 70 miles by line wire
9. To the London operator

*Courtesy of the Literary Digest*

the United States talks with London.

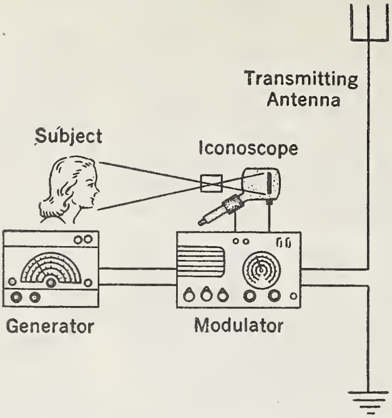


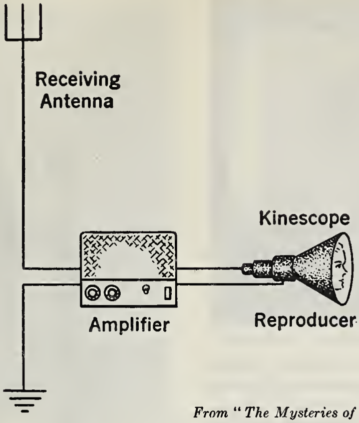
Fig. 784. Diagram to show the modern method used in televising. The comes from the Greek and means "image observer." The

word meaning "seeing," a transmitting and a receiving apparatus are needed, just as in the case of radio. Pioneers in television used the photo-electric cell and the *neon lamp*. The latter was used because it glows *instantly* when the current is turned on, and it goes out instantly when the current is turned off. Its brilliancy varies with the amount of current it receives.

1. *Transmission*. At the transmitting station. a powerful arc light was used to illuminate the person or object to be "seen." (See Fig. 784.) The light waves passed through the spirally arranged rows of holes in a disc turned by an electric motor. Since the disc made about 18 revolutions per second, spots of light struck the face, one at a time, until the entire area was covered. Such spots of light were reflected from the face to one or more photo-electric cells. Because such spots of light varied in intensity, they caused corresponding fluctuations in the current flowing from the photo-electric cells. The current was amplified and transmitted in the same manner as radio waves.

2. *The early receiver*. The waves were amplified at the receiving station and impressed upon a neon lamp. The brightness of the lamp varied instantly in just the same manner that the current varied in the photo-electric cell. A disc, an exact duplicate of the one used for transmission, was turned by a motor at exactly the same speed as the disc at the transmitting station. The rays from the neon lamp passed through the holes in the revolving disc to be viewed by the person at the receiving station. Those flashes of light had the same relative brightness as the light spots reflected to the photo-electric cell. Duration of vision lasts for about $\frac{1}{16}$ of a second. Just as the retina of the eye is able to form a composite picture of some 20 or more pictures flashed upon a screen, so the eye is able to scan an area mapped by spots of light, and blend them into a composite picture.

3. *The modern transmitter*. A few



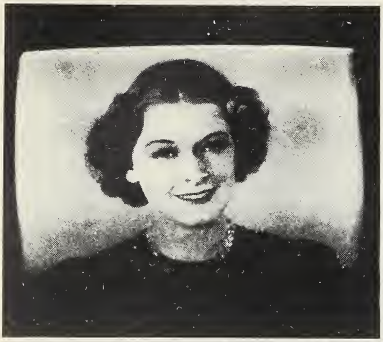
*From "The Mysteries of Television" by Arthur Van Dyck*

iconoscope is the essential part of sight transmission. Its name kinescope is the heart of the receiving system in television.

practical television sets were marketed before World War II began. This war retarded the expansion of television broadcasting, but engineers seem to be certain that the work will proceed rapidly as soon as the war ends and the process of post-war reconversion begins.

In the present method of transmitting, a camera lens is used to focus an image of the object to be televised upon a screen which consists of a large number of tiny photo-electric cells in the bulb of a large vacuum tube. This vacuum tube is called an Iconoscope. Through the neck of the vacuum tube an intense electron stream enters, and it is so directed that it scans the entire image. This electron stream sets up electrical impulses in the photoelectric cells. Such impulses are amplified and broadcast in the usual manner.

4. *The modern receiver.* At the receiving station the electric waves are amplified and transmitted to a modified cathode ray oscillograph. (See Fig. 750.) In such an apparatus the electric waves influence the stream of cathode rays by so bending them that they reproduce upon a fluorescent screen the image of the object which was focused upon the photo-electric cells at the transmitting station. Research engineers have now learned how to produce not only a black and white picture but also colored television, similar to colored motion pictures. One pair of the metal plates bends the cathode rays upward and downward, and a second pair, set at right angles, bends the stream from side to side. A new picture is painted, 30 times per second, on 525 lines, each a fraction of an inch below the other. It is expected that the 1000-line screen, which will produce better pictures, will be available soon. The spot from the electron stream covers the screen so quickly that the eye sees the entire picture at one time. (See Fig. 785.) It will be interesting to watch an athletic event as one listens to the voice of the announcer.



Courtesy of R.C.A. Manufacturing Company, Inc.

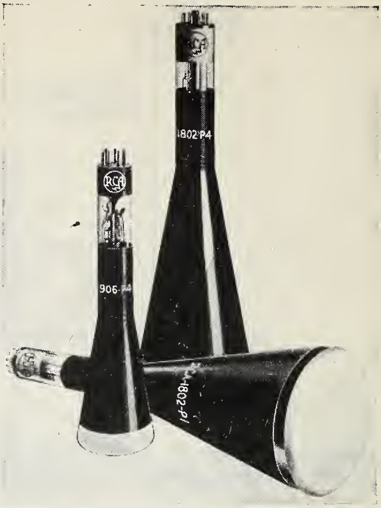


FIG. 785. The recent television picture above was drawn in 441 lines to an inch by a stream of electrons beating against a fluorescent screen on the end of one of the Kinescope tubes shown at the right. The millions of electrical impulses transmitted from the Iconoscope tubes of the National Broadcasting Company's television station in the Empire State Tower are changed into the lights and shadows that form the moving image. By increasing the number of lines produced by the electron streams, the clearness and continuity of the picture is improved. The new television sets furnish a picture large enough to be seen several feet distant. It may be viewed in a horizontal position, or it can be reflected upon a vertical screen.

## 4. Radio-Activity

**683. What is radio-activity?** In 1896, Henri Becquerel, a Frenchman, performed an epoch-making experiment. He found that a piece of metallic uranium darkens a photographic plate, even when the plate is wrapped in a piece of opaque paper and kept in the dark. Hence he concluded that uranium gives off *radiations* similar to X rays. Such radiations pass through substances opaque to ordinary light, but they are stopped by bones, metal, etc. Substances that give off radiations of this nature are said to be radio-active.

**684. How was radium discovered?** Soon after this discovery by Becquerel, M. and Mme Curie began a series of experiments to determine whether other elements show radio-activity. Of the elements known at that time, thorium, an element used in making Welsbach gas mantles, was the only one that exhibited this property. (See Fig. 786.) Mme Curie did find, however, that pitchblende, the mineral from which uranium is extracted, is four times as active as the pure uranium. Therefore she concluded that pitchblende must contain some other element more active than uranium itself. She patiently worked over several tons of pitchblende and succeeded in isolating a few milligrams of the chloride of an element that is more than 1,000,000 times as active as uranium. She named the element *radium*. Radium is usually used in the form of its salts; the chloride, bromide, or carbo-

Culver Service

FIG. 786. Marie Sklodowska Curie (1867–1934) was born in Poland. After Henri Becquerel discovered the radio-activity of uranium, Mme Curie, in collaboration with her husband, Pierre Curie, examined other materials to learn whether they were radio-active, too. She isolated radium. The Curies shared the Nobel prize in physics in 1903 with Becquerel. The college women of America gave her a gram of radium to carry on her scientific work.

nate, for example. Mme Curie succeeded, several years later, in 1910, in isolating metallic radium. Both the metal and its salts give off the *Becquerel rays.*

In 1921, Madame Curie visited the United States of America. The sum of $120,000 had been raised by subscription among the women of the United States for the purchase of one gram of radium bromide. This gift of the American women was presented to Madame Curie by the President of the United States.

**685. What is radium and what does it do?** In many respects radium is the most interesting element ever discovered. Its properties are unusual and it *does* things.

1. It *affects a photographic plate,* even through opaque substances like paper, wood, and *thin* sheets of metal. (See Fig. 755.)

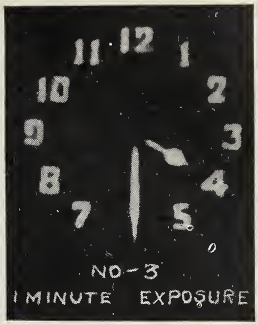


FIG. 787. Radium salts are used to coat the hands of watches and clocks and the dials of instruments that are used for night work.

2. Radium and its compounds *discharge an electroscope;* they knock to pieces the surrounding air molecules, breaking them up into ions and thus making them conductors. The activity of a sample of radium bromide may be determined by the rate at which it will discharge an electroscope of the type shown in Fig. 568. The electroscope is many times as sensitive for determining the value of radium salts as a chemical balance, even one weighing to 0.00001 gm.

3. Radium salts produce *fluorescence* with certain salts, just as X rays do. Hence, a mixture of a very small quantity of radium bromide and zinc sulfide is luminous in the dark. Such a mixture is used as a luminous paint for coating the dials of airplane instruments, the hands and dials of watches, and the sights of guns that are used for night firing. (See Fig. 787.)

4. Radium is *active chemically;* it decomposes water, changes oxygen to ozone, imparts a purple color to glass, etc.

5. The *physiological effects* of radium

are pronounced. It may destroy the germinating power of seeds, kill bacteria, or even destroy small animals. Radium produces frightful burns that require a long time to heal. Some early investigators were severely burned by radium while experimenting with it.

6. The salts of radium *glow in the dark*, producing a pale phosphorescence. In the daylight they resemble common table salt in appearance. They do not give off light enough to be observed in ordinary daylight.

7. Radium *gives off enough heat* every hour to melt 1.5 times its weight of ice, or about 120 calories per gram. This heat is given off quite continuously, since radium loses only one half its energy in the first 1700 years, one half of what remains in the next 1700 years, and so on.

8. Radium is rare and expensive. From new ores discovered in the Belgian Congo and from more recently discovered deposits in Northern Canada, radium salts can be extracted more cheaply than from the pitchblende or carnotite ores; the present price is about $25,000 per gram. *Radium is always found in uranium ores.* In fact it is now known that *uranium is the parent of radium.* But in radium ores, there is only about 1 part of radium to a little more than 3,000,000 parts of uranium. To produce 1 gram of radium several tons of the ore must be used. Large evaporating dishes are used to carry out the 75 successive crystallizations needed to separate radium salts from those of barium.

**686. What is the nature of Becquerel rays?** The Becquerel rays that are emitted by such elements as uranium, thorium, and radium have been very carefully studied. In 1899 Ernest Rutherford, then of McGill University, discovered that Becquerel rays are complex, consisting of three different classes:

1. The $\alpha$ rays, or *alpha rays*, are identical with *positively* charged helium atoms. Their mass is nearly four times that of the hydrogen atom; their velocity is from 10,000 to 20,000 miles per second. The alpha rays do not have as great penetrating power as the other rays; a very thin piece of aluminum foil or a thin sheet of paper is sufficient to intercept them. On the other hand, they are very efficient in ionizing air molecules; hence they discharge an electroscope rapidly. Severe radium burns are largely due to the alpha rays.

2. The $\beta$ rays, or *beta rays*, are identical with cathode rays. They consist of negatively charged particles of matter, or electrons. They are only about $\frac{1}{1840}$ as heavy as the hydrogen atom. Since they travel at a velocity of from 60,000 miles per second to 160,000 miles per second, they have much greater penetrating power than the alpha particles. The $\beta$ ray seems to be identical with the charge carried by the negative ion in solution, or during electrolysis.

3. The $\gamma$ rays, or *gamma rays*, appear to be of the same nature as X rays. They are more penetrating than either the alpha or the beta rays. The gamma rays are believed to be caused by the impact of beta particles upon surrounding matter. Fig. 788 shows the effect of a powerful magnetic field on the complex Becquerel rays emitted from a small amount of radium. The heavy alpha particles are deflected slightly in one direction; the lighter beta particles are deflected more markedly in the other direction; the gamma rays are not deflected at all. By the use of such

a magnetic field, Rutherford learned the nature of the Becquerel rays.

**687. What is the spinthariscope?** In 1903, Sir Wm. Crookes devised a little instrument called the *spinthariscope;* by the use of this instrument, it may be shown that particles are being continually emitted from radium. A speck of radium is mounted over a zinc sulfide screen. As the particles emitted by the radium strike the screen, they produce fluorescence. When the screen is examined in the dark by the use of a lens, a succession of sparks is seen. Each flash is produced by the impact of an alpha particle on the screen.

**688. The radium atom disintegrates.** Because heat and light appear to be given off continuously from radio-active substances without any apparent loss of weight, it was at first believed that radium is an exception to the law of the conservation of matter and energy. More careful investigations show that radium does slowly lose its energy, one half in the first 1700 years.

The question naturally arises, "What is the source of all this energy?" A long series of experiments has furnished the answer to this question. *The atoms of radium and other radio-active elements are exploding or disintegrating.* The alpha and the beta rays are the products of atomic disintegration. *Spontaneously* certain heavy atoms are breaking down into simpler and lighter atoms. After an average life of 2500 years, for example, the radium atom explodes. The radium atom is 226 times as heavy as the hydrogen atom. When it explodes, it loses an alpha particle, which becomes an atom of helium when it loses its charge of electricity. This helium atom weighs four times as much as the hydrogen atom. The remainder of the atom, 222

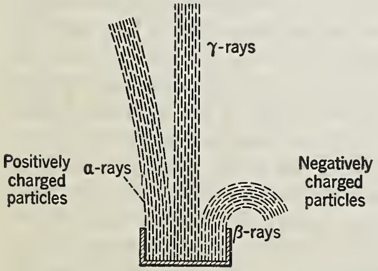

γ-rays
Positively charged particles
α-rays
Negatively charged particles
β-rays

FIG. 788. The effect of a magnet on the various types of radium rays.

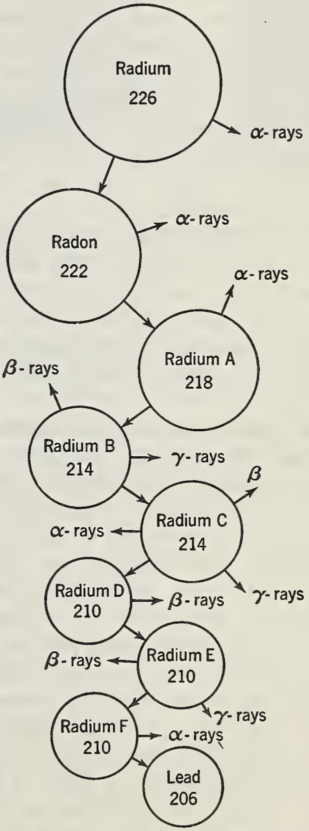

Radium 226
α-rays
Radon 222
α-rays
α-rays
Radium A 218
β-rays
Radium B 214
γ-rays
β
Radium C 214
α-rays
Radium D 210
β-rays
γ-rays
Radium E 210
β-rays
γ-rays
Radium F 210
α-rays
Lead 206

FIG. 789. The manner in which radium atoms disintegrate.

times the weight of the hydrogen atom, is a gas known as *radon*. Thus two gases, helium and radon, are formed when an atom of radium explodes. The beta particle is so light that its effect on the weight is slight.

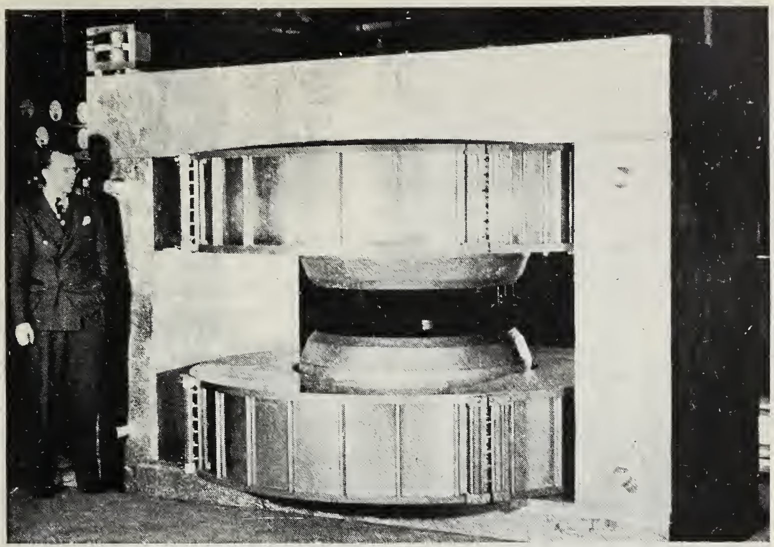
Radon loses half its activity in a little less than 5 days. At Memorial Hospital in New York four grams of radium are kept in vaults. The radon which is produced by the disintegration of this radium is used for treating cancerous growths. *Radon* forms *radium A* when it disintegrates. As radium *A*, which is radio-active, breaks down, it forms successively the radioactive elements *radium B*, *radium C*, *D*, *E*, and *F*. Radium *F* loses an alpha-particle and forms an element that has an atomic weight of 206; it seems to be identical with lead. (See Fig. 789.) Thus while uranium is the parent of radium, its descendant is lead. Chemists scoffed at the idea of the old alchemists that one element could be transmuted into another; now they learn that *spontaneous transmutation* is going on constantly with certain elements.

**689. Can atomic energy be utilized?** We have learned that one gram of good coal in burning yields about 8000 calories. It is possible to compute the amount of heat liberated by one gram of radium when disintegrating, since we know that one gram yields about 120 calories of heat per hour throughout an average life of about 2500 years. The total amount is more than 300,000 times as much heat as can be obtained by burning an equal weight of coal.

J. J. Thomson has estimated that the energy stored in one gram of *hydrogen* equals 6 × $10^{11}$ foot-pounds. Thus the energy in less than ½ oz. of hydrogen would be sufficient to lift 10 of our largest battleships (32,000 tons each) higher than the top of Mt. Blanc. over 3½ miles. Whether man will ever learn how to unlock this tremendous storehouse of energy and put it to practical use is problematical. If scientists fail to find the secret, it will not be for want of much experimental work. Atom-smashing at the present time is one of the favorite problems in many universities.

**690. How are atom-smashing machines constructed?** The first atom-smashing machine was built by Professor Lawrence of the University of California. It was called a *cyclotron.* The first one was rather small, but they have been increasing in size, until one now in use has an electro-magnet which weighs 85 tons, and the faces of its magnetic poles are more than 3 ft. across. A cyclotron with an electro-magnet of 220 tons is being constructed. If we stop to consider that the largest atom is not more than one hundred-millionth of an inch in diameter, then the use of so huge a machine for atom-smashing seems not unlike using an elephant to help us destroy a tiny gnat.

Atoms, as we know, are made up of protons and electrons. Because nearly all the mass of the atom is concentrated in the positively charged nucleus, we must split the nucleus in order to smash the atom. Protons may be used as projectiles to bombard the nuclei of the atoms, which serve as targets. A proton has the same weight as the nucleus of the hydrogen atom. Sometimes *deuteron*, which is the nucleus of the heavy hydrogen atom, is used to bombard the targets. The deuteron particle is twice as heavy as a proton. In the machine designed by Lawrence, the target used is made of beryllium.



*Courtesy of the General Electric Company*

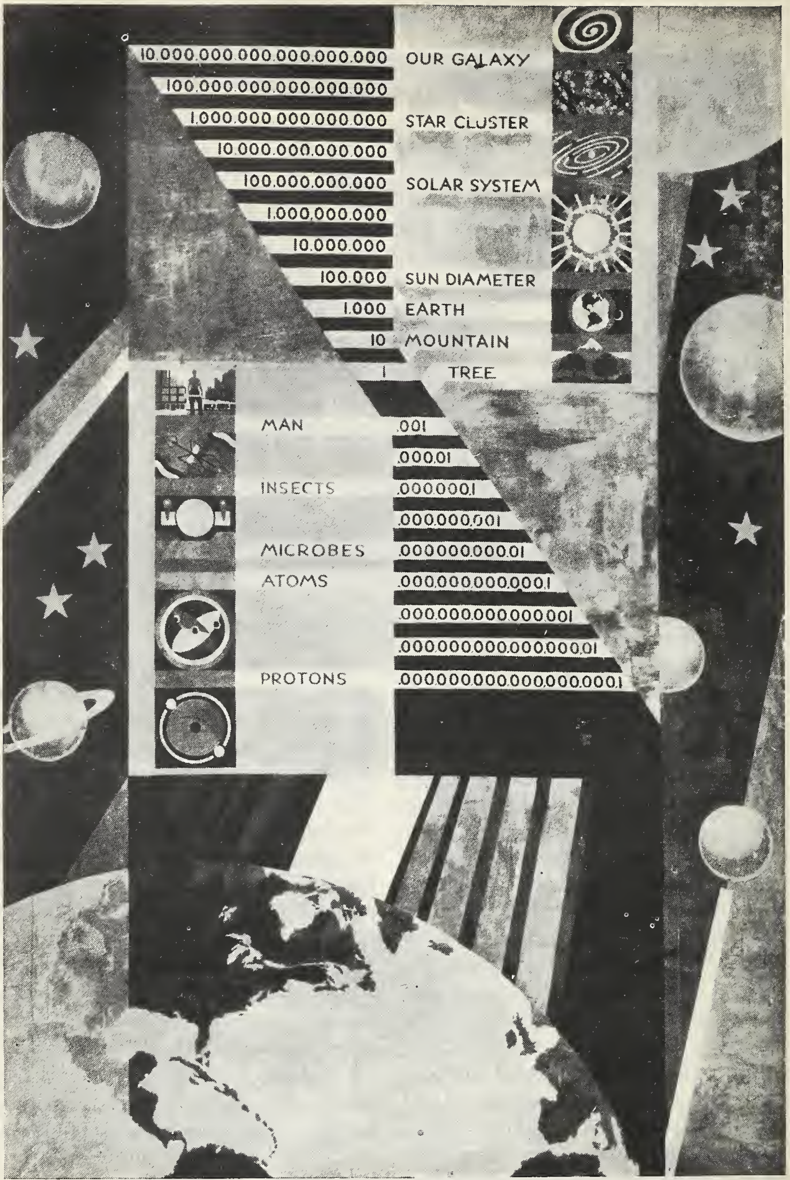
FIG. 790. The cyclotron is used as an atom-smashing machine.

A cylindrical box is placed between the poles of a huge electro-magnet and exhausted until a high vacuum is produced. The deuterons which enter the center of the cylindrical box are forced toward the outside of the box by a potential of some 50,000 volts which is set up between two electrodes on the side of the box by means of a radio-frequency oscillator. The field of the electro-magnet pulls them around in a spiral. After each half revolution, the reversal of the voltage gives these tiny bullets a tremendous impetus. Thus they keep moving faster and faster until they reach the outer rim of the box, where at a pressure of nearly 8,000,000 volts they strike the beryllium target.

Several cyclotrons have been built for use at our large universities in the United States and several are in use in Europe. More are being built. Special devices are used to identify the fragments of the atoms.

**691. What do the cyclotrons accomplish?** When Rutherford first began bombarding atoms in an effort to disintegrate them, he used alpha particles from some radio-active substance. (See Fig. 790.) The modern cyclotron when operating at a high voltage probably hurls as many projectiles at a target as all the radium in the world could produce by its normal disintegration.

In some cases, the projectiles score a direct hit and the nucleus of the atom is split up into fragments. These fragments may combine to form an atom of a different weight. Hence it is possible to have transmutation of the elements, despite the fact that chemists for a long time scoffed at this view of the old alchemists. Sometimes the projectile hits the nucleus and combines with it. Such a nucleus may be unstable and begin to give off particles in the same manner that any radioactive element does. Such an element


10.000.000.000.000.000.000 OUR GALAXY
100.000.000.000.000.000
1.000.000.000.000.000 STAR CLUSTER
10.000.000.000.000
100.000.000.000 SOLAR SYSTEM
1.000.000.000
10.000.000
100.000 SUN DIAMETER
1.000 EARTH
10 MOUNTAIN
1 TREE
MAN .001
.000.01
INSECTS .000.000.1
.000.000.001
MICROBES .000.000.000.01
ATOMS .000.000.000.000.1
.000.000.000.000.001
.000.000.000.000.000.01
PROTONS .000.000.000.000.000.000.1

*Courtesy of Museum of Science and Industry, Chicago*

FIG. 791. This illustration shows us the relative sizes of various objects, of those too small to be seen even by the ultra-microscope.

is said to be *artificially radio-active.* It is interesting to learn that Mme Curie, in collaboration with her husband, discovered radium. Her daughter, Iréne, in collaboration with her husband, M. Joliot, discovered artificial radio-activity. Scores of radio-active elements have been made by bombarding nearly all the elements with atom-smashing particles. (See portrait, Fig. 786.)

**692. What are neutrons and positrons?** In our earlier study of the structure of the atom, protons, neutrons, and electrons were mentioned. In the year 1932, Chadwick in England discovered that the nuclei of some atoms contain one or more *neutrons.* The neutron particle has approximately the same weight as the proton, but it does not carry any electrical charge. By some physicists the neutron is believed to be the result of an intimate union between a proton and a negative electron. It is useful as a projectile in bombarding atoms, because it requires less energy to shoot a *neutral* particle into a *positively* charged nucleus than to shoot into the nucleus a *positively* charged proton or deuteron. (See cover design.)

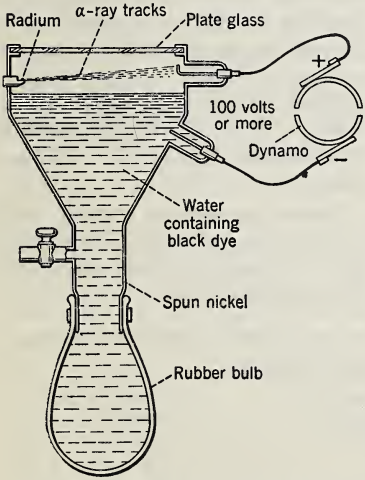
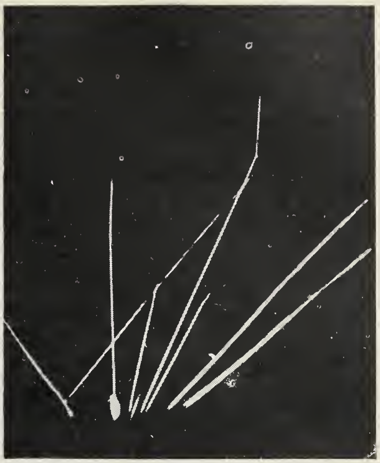


FIG. 792. The Wilson cloud chamber is much used to study the nature of the particles formed by "smashing" atoms.



*Science Service*

FIG. 793. The track of an alpha particle as shown on the screen of a Wilson cloud chamber.

About six months after the discovery of the neutron, Dr. Carl Anderson discovered the *positive* electron. This tiny particle, which is known as the *positron,* has almost the same mass as the negative electron, which is approximately $\frac{1}{1840}$ that of the hydrogen atom. Before the discovery of the positron, the proton was believed to be the smallest unit of positive electricity. From the smashing of atoms and the study of their fragments by the Wilson cloud chamber, scientists are finding that the nucleus of the atom, with its protons, neutrons, etc., is more complex than it was formerly supposed to be. In Fig. 791 we have a copy of one of the murals used at the Century of Progress. It shows some of the relative sizes of things in our universe.

**693a. How is a Wilson cloud chamber used?** A method for studying ionization is based upon the work of C. T. R. Wilson. The lower part of an inverted cone and rubber bulb is filled with water dyed nearly black. In the upper compartment of the apparatus there is a tiny bit of radium in a glass capsule. Some source of current is used to maintain a voltage of 100 or more across the air space in the upper compartment, which is artificially illuminated. (See Fig. 792.)

When the rubber bulb is squeezed, the air is compressed. As it is released, the air expands and tracks of alpha particles can be seen through the glass, reflected from the dark background. They become visible because they ionize the air molecules, and particles of fog condense upon them. The alpha particle tracks come out from the tip of the capsule in which the radium is enclosed. (See Fig. 793.)

By means of such a cloud chamber, one can identify the fragments of atoms from the tracks which the particles make when the atoms disintegrate.

**693b. How is radar used?** It is rather interesting that a radio beam follows the curvature of the earth. At an altitude of 60 or more miles above the surface of the earth there is a kind of roof composed of electrically charged particles, and known as the Kennelly-Heaviside layer. Radio waves strike it and rebound. The idea of radar as a detector and locator of distant objects arose from the fact that some object, a ship for example, moving between the transmitter and receiver, interferes with radio waves. The radar instrument, whose innermost secrets are carefully guarded, contains the following elements: (*a*) a short-wave transmitter which is turned alternately on and off almost instantaneously, sending out a radio wave which strikes any object in its path and is reflected back in a few millionths of a second; (*b*) a short-wave receiver which receives the reflected wave and measures the time it takes the wave to travel to and from the object. Since radio waves travel about 186,000 miles per second (the speed of light), the distance to the object may be determined by the receiver; (*c*) the antenna through which the transmitter sends the waves and through which the receiver receives the echoes from the object. The antenna is rotatable. It sends and receives waves only in the direction in which it is pointed. Thus by knowing the direction in which the antenna is pointed, and the range, or distance, which is measured by the receiver, it is possible to determine the accurate position of the object, or target.

Radar instruments are now being used to direct the fire of antiaircraft guns. It is probable that radar will find many peacetime uses, too.

*How many of the following terms can you define or explain? (In this chapter we have been introduced to the newer physics.)*

Cathode rays
Marconi
Cosmic rays
Audion tube
Carrier wave
Detector tube
Radio compass
Photo-electric cell
Radio-activity
Mme Curie
Neutron
Deuteron
Oscillograph
Lee De Forest
Filament circuit
Plate circuit
Screen-grid tube
Television
Becquerel rays
Cyclotron
Positron

# Unit Twelve

# *Transportation*

## Preview

As early as 1680, Sir Isaac Newton proposed the idea of a steam-driven vehicle. Such a vehicle was built by Nicholas Joseph Cugnot in 1790. When Robert Trevithick built a steam carriage in 1802, he was not permitted to drive it on the streets in England unless someone walked ahead to warn pedestrians, because it could make the excessive speed of twelve miles per hour. In our craze for speed and more speed we have progressed too far in the opposite direction. In an hour the modern automobile can travel what was considered in colonial times a day's journey.

If you scan the table of contents of any book in physics, you will find it difficult to discover a single chapter which does not include some principle of physics that is utilized in the manufacture or operation of the automobile. You will find efforts to increase friction where it is needed and to reduce friction where it is not wanted. You will find the principles of heat applied in the cooling system and in the operation of the engine. You will find efforts made to produce proper lighting without glare. You will find levers and other simple machines in considerable profusion. Without a generator to charge your battery and without a storage battery to supply electricity for the self-starter, the horn, the lights, and the ignition, a car would not run at all. In fact, after a course in physics one could very well use the study of the automobile as a review of the entire course. A few new topics are included in this unit.

Probably many of you are becoming "air-minded." Planes are now being made which are larger, stronger, faster, and safer than they have ever been before. Statistics seem to indicate that a passenger may be likely to fly for at least a million miles without the probability of an accident. In

World War II the problem of transportation is more important than ever before. It takes about seven ships to transport the food, munitions, tanks, jeeps, motor trucks, and artillery for one shipload of fighting men. The tanks, or land battleships, have been very effective, but more than ever modern war is a war of the air. Light bombers and heavy bombers drop their loads from elevations of 30,000 feet. Fighter planes and dive bombers fly at speeds of 350 to 500 miles per hour.

# *The Automobile — The Airplane*

## 1. The Automobile

**694. Transportation depends on the principles of physics.** Every few days we read in our newspapers that someone has driven an automobile faster than ever before, or that someone has clipped a few more minutes from the record time for flying across the continent or the ocean. This craze for speed is not to be lauded, but it is the work of scientists that makes it possible. We are more interested in the fact that modern physics makes it possible to build a car or a plane that will be almost foolproof, that can be depended upon to operate consistently and safely, and that is both durable and comfortable.

**695. The automobile has three parts.** For convenience, we may consider that the automobile consists of three parts: (*a*) *the power plant;* (*b*) *the chassis, or running gears;* (*c*) *the body.* In our study of each one, we shall pay especial attention to the physical principles that are utilized.

**696. The power plant has been improved.** We have already learned how a gasoline engine works. The first engine, invented by Lenoir, a Frenchman, was very wasteful because the gasoline vapor was not compressed before it was ignited. The compression stroke was added by Otto, a German, about eighteen years later. It cut the gasoline consumption to about one-third that of Lenoir's engine.

Since the automobile became practical, men have seen the gas engine grow from a single-cylinder power plant, which required a 300-lb. flywheel to keep it going between successive power strokes, to the two-cylinder engine, the four-cylinder, and finally to the straight eight or the V-eight which is now found in many engines. To secure very great flexibility, sixteen-cylinder engines are in use in some heavy cars.

In addition to increasing the number of cylinders in the power plant, the

---

### Vocabulary

CARBURETOR, a device used to vaporize gasoline and mix it with enough air to form an explosive mixture.

CLUTCH, a device to connect the engine shaft with the drive shaft.

TRANSMISSION GEARS, sets of gear-wheels used to vary the speed of a car, and to reverse the car.

DIFFERENTIAL, a device used in the divided rear axle to permit one rear wheel to turn faster than the other.

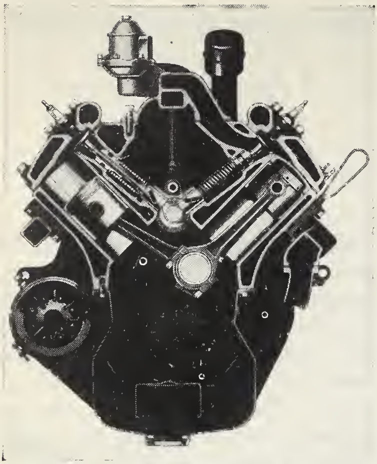
DISTRIBUTOR, a device used to distribute the spark to the cylinders in the proper order and at exactly the right time.

CEILING, a term used by aviators to indicate the height of clouds or mist below which objects are visible.

AILERON, the name given to a small plane hinged to the rear of an airplane wing.

AIRFOIL, a name given to the wing of an airplane.

NACELLE, a closed compartment provided for pilot or passengers or for the power plant of an airplane.

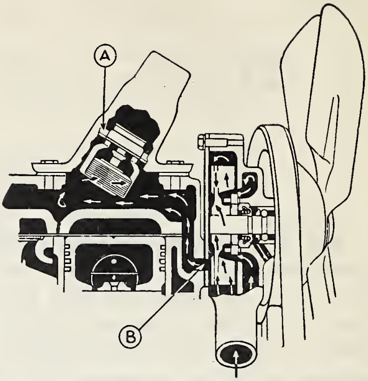


*Courtesy of the Ford Motor Company*

Fig. 794. Cutaway view of an eight-cylindered automobile engine.

compression ratio has also been increased. This increases the efficiency of the engine. At one time a compression ratio of 4 to 1 or 5 to 1 was common. Now, the refining of gasoline to give it a high octane rating makes it possible to increase the compression ratio in some of the new engines to 6 to 1 or 6.5 to 1. For such engines, a gasoline having an octane number of 70 or more is desirable to prevent engine knocks. (See Fig. 794.)

**697. The cooling system is important.** In our study of the gas engine, we learned that it is necessary to keep an engine reasonably cool by the circulation of water around the cylinders and through the head. There is not likely to be much trouble with the cooling system in summer, but winter brings its problems. A thermostat remains closed until a small quantity of water is warmed and then opens to permit the water to circulate around the radiator. (See Fig. 795.) This permits the engine to warm up quickly.



*Courtesy of the General Motors Corporation*

Fig. 795. The thermostat is shown here in the closed position, and only a small amount of water is being warmed. When it opens, the circulation becomes general.

If the water freezes, it may burst the cylinder head, the water jacket, or the radiator. Hence, an *anti-freeze* solution is necessary. An ideal anti-freeze solution does not rust the metal parts or destroy the rubber connections. It must have a low freezing point. It must not boil away too rapidly.

A mixture of alcohol and water is not very expensive, and it has a low freezing point. It does not corrode the metal parts, but it may spoil the finish of the car if it overflows and comes into contact with the lacquered parts. Unfortunately, it boils away quickly, and it boils away faster than water does. Hence, a motorist may have a sufficient proportion of alcohol in the radiator mixture before starting on a trip, and boil away so much alcohol during the trip that the freezing point of the mixture becomes too high. A mixture of 30% *alcohol* and 70% *water* has a freezing point of about − 1° F.

Glycerine and water make a fairly satisfactory anti-freeze solution. The glycerine does not boil away. It does attack rubber hose connections, however, and it leaks through such tiny openings that it is difficult to prevent loss of the solution by leakage. It is difficult to believe that the viscous glycerine will go through a smaller opening than alcohol will, but it is true. Glycerine is rather expensive, too. A rather permanent mixture containing 15% *alcohol*, 15% *glycerine*, and 70% *water*, freezes at – 5° F. Government authorities have recommended the use of *ethylene glycol* as an antifreeze that is as satisfactory as glycerine, and less expensive.

**698. How does gasoline get to the engine?** In early models, the gasoline tank was under the front seat and the gasoline flowed down to the carburetor by gravity. Later, a vacuum tank was used. Now, nearly all cars have a fuel pump to pump the gasoline from the tank in the rear through a metal pipe beneath the car to keep the carburetor supplied.

**699. What is the purpose of the carburetor?** Contrary to popular belief, *liquid* gasoline does not explode. *Gasoline vapor does not explode, unless it is mixed with air.* When mixed with air in the proper proportion, gasoline vapor forms an explosive that is many times as powerful as an equal weight of dynamite. The carburetor is designed to vaporize the gasoline and mix it with enough air to form an explosive mixture. An *ideal* carburetor should be so constructed that it will vaporize every drop of gasoline and mix it with enough air to burn completely every molecule of the vapor. For three reasons, such a carburetor is impossible:

1. Gasoline is a mixture of varying composition. One sample may need 47 parts of air to one of vapor for complete combustion, and another sample may require 60 parts of air.

2. Perfect vaporization cannot be secured until the engine warms up, and a richer mixture of gasoline is needed for starting.

3. A carburetor that is adjusted for one speed of operation is not perfectly adjusted when the engine is running more rapidly.

**700. How does the carburetor work?** Look at Fig. 796. One part of the carburetor consists of a gasoline well, which is kept filled to the level shown in the figure by means of a float which controls the needle valve at the end of the tube leading from the gas supply tank. When the engine operates, a partial vacuum is produced in the chamber shown in the figure. The throttle is opened. Air entering in the direction shown by the arrows sweeps past the end of the nozzle and mixes with the gasoline vapor which is escaping from it. The space around the nozzle is narrowed so that the air will have a greater velocity. An auxiliary valve may be used to open automatically and admit more air when the engine is running rapidly.

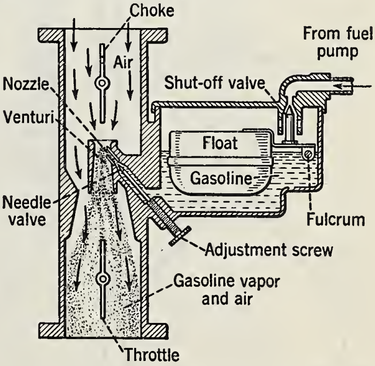


Fig. 796. The carburetor vaporizes the gasoline and mixes it with air to form an explosive mixture. Downdraft type.

**701. What is the purpose of the choke?** A mixture of gasoline vapor and air containing more gasoline vapor than is necessary to form an explosive mixture is often called a "rich" mixture. One containing a larger proportion of air is called a "lean" mixture. It is economical to have the carburetor so adjusted that the engine will run on the "leanest" possible mixture. Such an engine stalls easily, and it is hard to start in cold weather. A choke may be used to shut off some of the air supply entering the carburetor and give a richer mixture. (See Fig. 796.)

The choke should be used in starting. Then the choke button should be pushed back again to admit free entrance of air as soon as the engine is warmed up. On many new cars the choke is automatically operated. It is wasteful to use the choke after the engine is warmed up, and it fouls the cylinders of the engine. It is not a good plan to use the choke to stop the engine in the evening in order to have it start more easily the next morning, because the vapor will condense on the cylinder walls and dissolve the oil film which keeps them lubricated. In that way the walls might be scored.

**702. What part of an automobile is the chassis?** By the *chassis* we mean the frame to which the body and the wheels are attached, and the various parts of the drive mechanism. Sometimes the power plant, which has been discussed, is also considered a part of the chassis.

As new models appear from year to year, one observes that automotive engineers have steadily been making improvements. The engine is cushioned to prevent vibration. It is suspended low in its frame to give greater "roadability." A balancer is used on the crankshaft to secure steady motion. The frame is made stronger than ever before, by the use of special steels that are not likely to break, and also by special methods of bracing. The X-type frame is particularly strong. (See Fig. 797.) Crosswise tubes and heavier bumpers give more protection. The box-type frame is now being used by some manufacturers. (See Fig. 798.) With little more weight than the older type of frame made from channel steel, the box-type frame is much stronger. The frame is underslung to give greater stability and make the car less likely to overturn when rounding a curve, or when standing on a

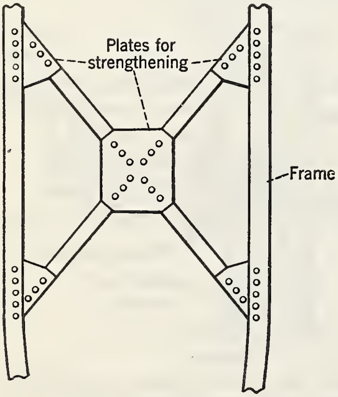


FIG. 797. The X-shaped frame is exceptionally strong.

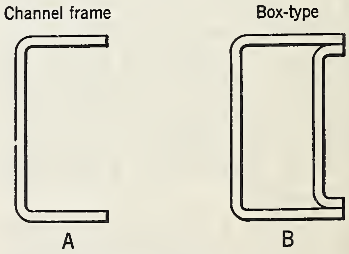


FIG. 798. The box-type of frame is stronger than the channel type.

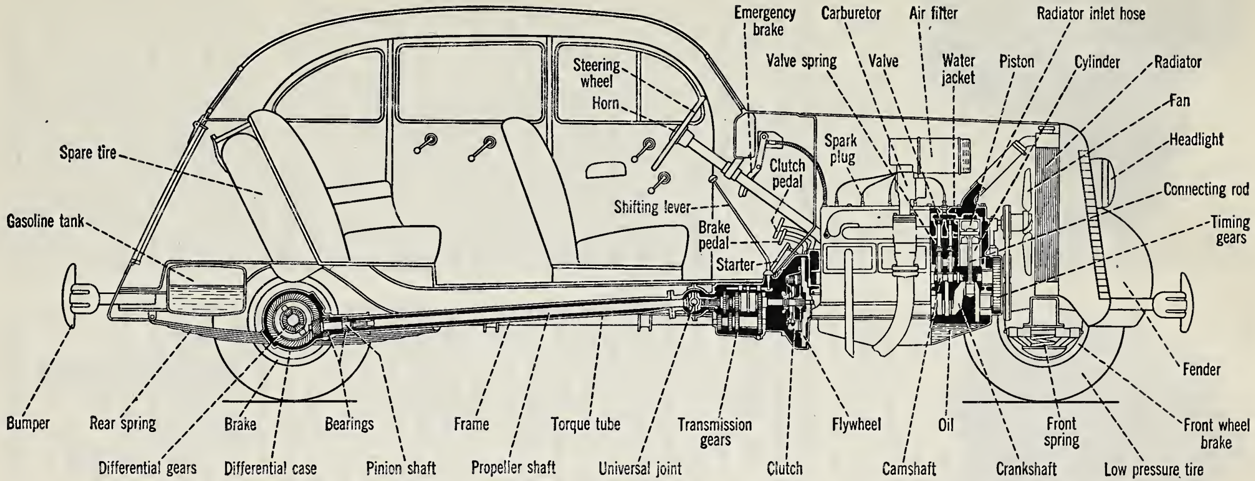

Emergency brake
Carburetor
Air filter
Radiator inlet hose
Steering wheel
Horn
Valve spring
Valve
Water jacket
Piston
Cylinder
Radiator
Fan
Headlight
Spare tire
Spark plug
Clutch pedal
Connecting rod
Gasoline tank
Shifting lever
Brake pedal
Starter
Timing gears
Fender
Bumper
Rear spring
Brake
Bearings
Frame
Torque tube
Transmission gears
Flywheel
Oil
Front spring
Front wheel brake
Differential gears
Differential case
Pinion shaft
Propeller shaft
Universal joint
Clutch
Camshaft
Crankshaft
Low pressure tire

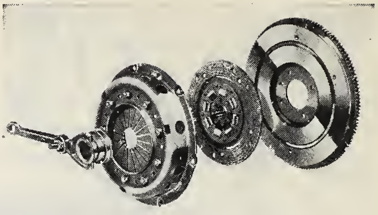
FIG. 799. The way an automobile would appear after being sawed lengthwise is seen in profile. It shows the position of the radiator, the fan, the engine, the crankshaft, the flywheel, the clutch, the transmission gears, the universal joints, the propeller shaft, the differential, and many other parts.

slanting road. The springs are encased in leather or metal to prevent the entrance of dirt and to insure better lubrication.

**703. What is the plan of the drive mechanism?** If one were to saw a car through the center from front to back, its profile would be found to resemble Fig. 799. In the extreme front we have the radiator, with the fan as a part of the cooling system immediately behind it. Then we have the engine, mounted on rubber pads and fastened securely to the frame. Beneath the engine is the crankshaft, and fastened to the engine is the carburetor. At the rear end of the crankshaft, which is mounted in several bearings to reduce vibration, we find the flywheel. A clutch is used to connect the crankshaft with the driven part of the car.

The clutch is connected to the transmission gears, which are used to vary the speed. A propeller shaft is used to connect the transmission gears with the differential in the rear axle. There are two universal joints in the propeller shaft to permit it to bend up and down, or from side to side. They are similar to the joints in our wrists, which permit freedom of motion in any direction. When the differential, which is mounted in the center of a divided rear axle turns, it causes the rear wheels to turn, too, and drive the car.

**704. How does the clutch work?** The gas engine does not start under load. Hence it must be disconnected from the rest of the car while it is coming up to speed. The following is the problem that engineers had to solve: Given a crankshaft spinning several hundred revolutions per minute. Also a drive shaft which is stationary. The two must be connected so that they will both revolve at the same speed, with as smooth an engagement of the two parts as possible. The answer to the problem is the *clutch*. (See Fig. 800.)

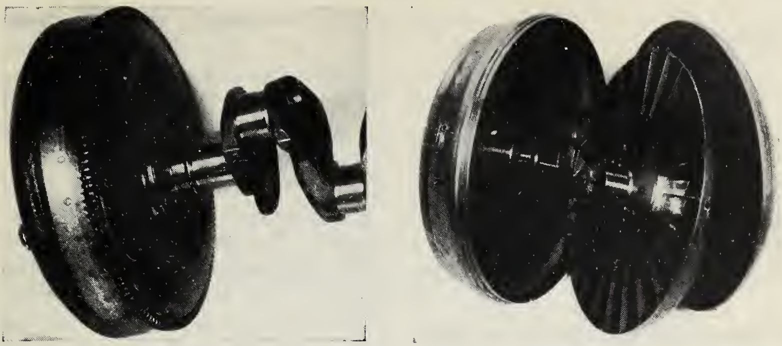


*Courtesy of Chevrolet Motors Sales Corporation*

FIG. 800. The clutch is used to connect the engine with the propeller shaft through the transmission gears.

Attached to the stationary shaft is a plate, or a series of plates, covered with a ring of "friction" material. This ring of friction material can be pressed up against the face of the flywheel by means of strong springs. A lever, operated by the left foot of the driver, can be used to *engage*, or to *disengage*, the clutch. When the left foot is pressed down against the clutch pedal, it pushes the clutch plate backward, and disconnects the crankshaft from the drive shaft. Then the engine "idles" or runs without driving the car. As the left foot is lifted from the clutch lever, the springs push the clutch plate forward to engage the clutch. The clutch should slip a little as it is engaged gently, and then hold firmly. A sudden engagement of the clutch results in a jerking motion.

The clutch is used in starting the car, in stopping the car, and when shifting gears. Trying to beat the other fellow away in traffic puts undue strain upon the clutch. Some drivers get the habit of "riding the clutch" by keeping the left foot upon the clutch pedal all the time when driving. The habit is a bad one, as a little unconscious pressure on



*Courtesy of the Chrysler Corporation*

FIG. 801. The liquid clutch is now used by some busses and one make of pleasure car.

the clutch means that the clutch may slip, and the friction material used as a clutch facing soon wears away.

**705. How does the liquid clutch work?** By the use of the newer liquid clutch, the necessity of shifting gears is avoided, except in reverse. As used on busses, it is unnecessary for the driver to operate a clutch in the ordinary way or to use a gearshift lever unless he wishes to back up. There is no jerking or stalling of the engine when the car equipped with such a clutch starts, and the car can be stopped, too, without killing the engine, merely by the use of the brakes.

With such a *fluid drive*, as it is called by one company, the crankshaft has at its end a set of blades something like a water wheel. Facing this water wheel is a second set of blades, mounted on the end of the transmission shaft. Both sets of blades are enclosed in a sealed housing filled with oil. As the engine picks up speed, the blades attached to the crankshaft through the flywheel set the oil in motion, and the moving oil sets the blades attached to the transmission shaft in motion as it impinges upon them. Thus the power is transmitted to the rear wheels through the liquid clutch. (See Fig. 801.)

**706. What are transmission gears for?** The throttle or accelerator is used to vary engine speed. Such control is satisfactory for driving on a level road. But to overcome the inertia of a car in starting or to drive the car up a steep hill, one needs a set of *transmission gears*. Most pleasure cars have three speeds forward and one speed in reverse.

The transmission system has three shafts: The pinion shaft, Fig. 802, and the propeller shaft are both in the same straight line. The countershaft is always connected at one end to the pinion shaft, and it may be connected by means of sliding gears with

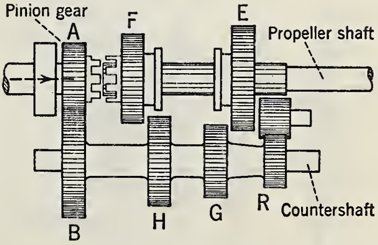


FIG. 802. Transmission gears in neutral.

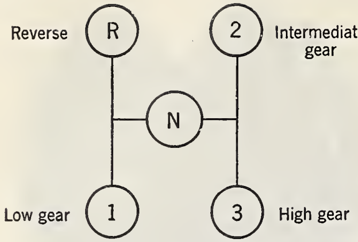


FIG. 803. H-shaped diagram to show gearshift.

the main drive shaft. The pinion shaft is connected to the engine through the clutch and it makes the same number of revolutions per minute as the crankshaft. Since the countershaft is geared to the pinion shaft, it is always in gear and it turns when the engine runs. The gear wheels, *E* and *F*, can be slid forward or backward along the drive shaft, which is square or grooved. Hence, when they turn, the main shaft must turn, too.

*Neutral.* In starting the engine, the gearshift lever is at the position *N* of Fig. 803. The gears are then in the position as shown in Fig. 802. The pinion gear and the countershaft both turn. The pinion gear turns at the same speed as the crankshaft, but the countershaft may turn faster, more slowly, or at the same speed as the crankshaft, depending upon the relative number of teeth in each gear wheel. For example, suppose that there are 30 teeth in gear wheel *A* and 60 teeth in gear wheel *B*. Then the countershaft turns only one half as fast as the crankshaft. The drive shaft and the rear wheels do not turn, because its gears are not "en mesh" with those of the countershaft.

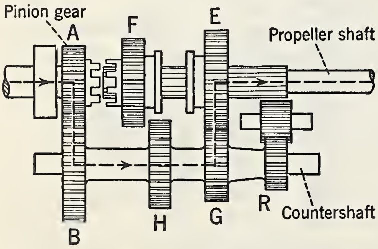


FIG. 804. Transmission gears for low speed.

*First speed, or low speed.* When the operator disengages the clutch and pulls the gearshift lever back to the position (1) of Fig. 803, he slides the gear *E* forward until it is en mesh with the small gear *G* on the countershaft. (See Fig. 804.) Suppose that *E* has 40 teeth and *G* has only 20 teeth. Then the drive shaft will make only half as many revolutions per minute as the countershaft, and only one fourth as many revolutions per minute as the crankshaft of the engine. We have two gear reductions, and the car is in *low gear*. At a given engine speed, it travels slowly. The power in this case is transmitted through *A*, *B*, *G*, and *E* to the drive shaft, or propeller shaft, as shown by the dotted lines.

*Second speed, or intermediate speed.* As the gearshift lever is shoved forward and slightly from the driver to position (2), Fig. 803, it moves the gear wheel *E* backward, and at the same time it moves the gear wheel *F* back until it is en mesh with the gear wheel *H*. (See Fig. 805.) Suppose that

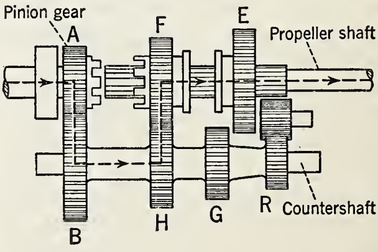


FIG 805. Transmission gears for intermediate speed.

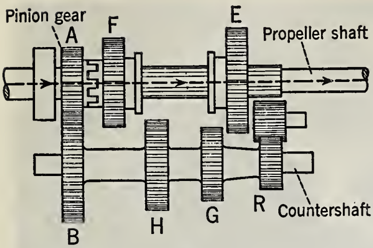


Fig. 806. Transmission in high gear.

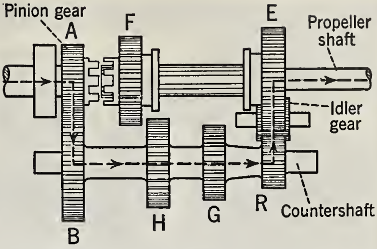


Fig. 807. Transmission gears in reverse.

gear wheels *F* and *H* both have the same number of teeth, then the countershaft and the drive shaft will both make the same number of revolutions per minute, both of them just half as many as the crankshaft. The dotted line shows how the power is transmitted through gear wheels *A*, *B*, *H*, and *F* to the drive shaft.

*Third speed, or high speed.* When the gearshift lever is pulled back to position (3) Fig. 803, the gear wheel is pushed forward until it is locked to the pinion gear by means of teeth on the sides of the two gear wheels. (See Fig. 806.) The drive is now direct through the crankshaft and the drive shaft to the rear wheels. Both make the same number of revolutions per minute. The countershaft is idling.

*Reverse speed.* When the operator of a car pushes the gearshift lever forward to the position *R*, Fig. 803, then the sliding gear wheel *E* is en mesh with a small idler gear and the gear *R*. (See Fig. 807.) Three gears are now en mesh as shown in Fig. 808. The pupil will observe that the crankshaft turns in the same direction as before, but the propeller shaft turns in the opposite direction.

**707. What is synchro-mesh transmission?** In shifting gears with the conventional transmission, the teeth sometimes "clash" or "grate," because it is difficult to "mesh" quietly the gears of two wheels traveling at different rates of speed. With *synchro-mesh* transmission the intermediate gears are always en mesh, and the intermediate gear revolves on a bronze bushing, which turns with the drive shaft. (See Fig. 809.) To engage this gear wheel a slider coupling with teeth on the outside is used. When shifting into intermediate gear, these teeth mesh with gears cut internally on the intermediate gear wheel. A cone-type clutch is used to bring the two gears up to the same speed, or to synchronize them, before they are engaged. To secure more quiet operation when driving in second gear, bevel gears are used.

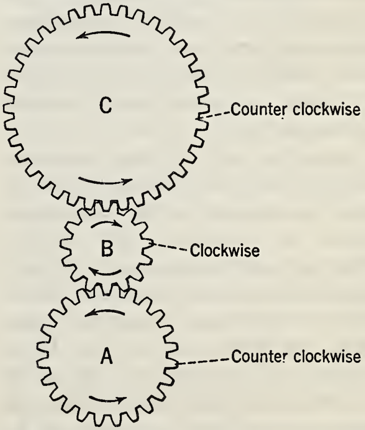
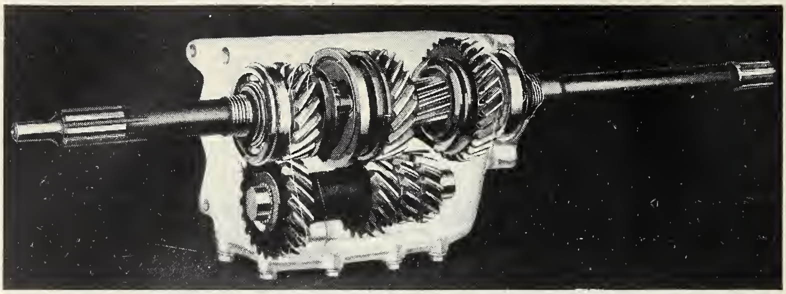


Fig. 808. The wheels *A* and *B* turn in opposite directions.



Courtesy of the General Motors Corporation

FIG. 809. Synchro-mesh transmission gears.

A second cone-type clutch is used to synchronize the slider coupling gear before shifting into high speed. The mechanism for shifting into low speed or into reverse is the same as that used with the conventional gearshift.

**708. What is the differential?** The transmission system is connected with the *differential* on the rear axle by means of two universal joints and the drive shaft. (See Fig. 799.) In rounding a corner, the outer wheel of a car must travel faster than the inside wheel. Since the driving power of the engine is transmitted to the rear axle, a device must be used so that the two rear wheels will both drive together; and it must permit one wheel to travel faster than the other on curves. The *differential,* which is placed between the two parts of the divided rear axle, accomplishes both of these purposes. (See Fig. 810.) The driving pinion, *A*, which is attached to the drive shaft, rotates the bevel gear, *B*, which is rigidly attached to the frame, *F*, and through the frame to the gears *C* and *E*. These parts must all rotate as a unit within the differential housing. On a straight road, the gears *C* and *E* do not rotate on their axes, but they are carried around with the frame, *F*. As they revolve with the frame, they turn the gears *D* and *G* at the same speed. These gears are attached to the inner ends of the divided rear axle. As they turn the axles, the rear wheels, which are rigidly attached to the other ends of these axles, drive the car. When the right axle turns faster than the left on a curve, then the gears *C* and *E* turn on their axes in opposite directions to compensate for the difference in speed of the two rear wheels. If one wheel stops, the other may continue to turn. A non-skid chain on one rear wheel is of no value on slippery roads. While

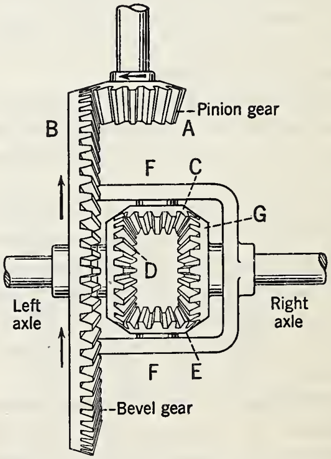
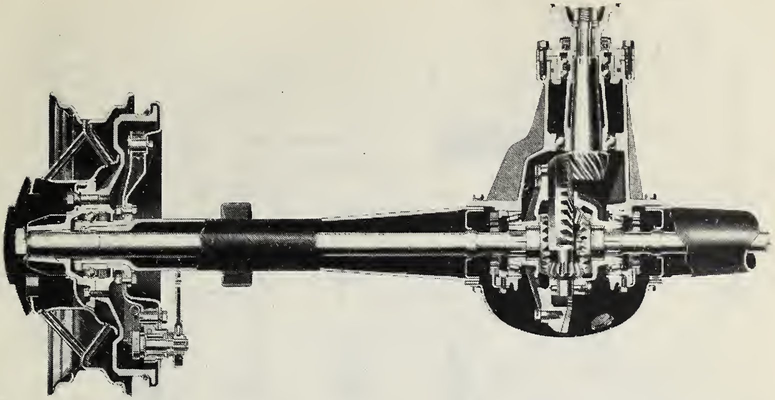


FIG. 810. Diagram of differential gears.



*Courtesy of Cadillac Motor Car Company*

FIG. 811. Differential and rear axle.

one wheel grips, the other spins around rapidly, but the car does not move.

We have already seen how the speed may be varied by means of transmission gears. There is a gear reduction in the differential. If the pinion gear has 15 teeth and the bevel gear has 65, then at high speed the engine will be making 65 revolutions while the rear wheels are making only 15. The *gear ratio* on such a differential is 4.33 to 1. Fig. 811 shows a sectional view of a rear axle with the housing cut away to show the differential. Some cars use a *dual gear ratio* in the differential. It is then possible to use one ratio to travel at very high speed and still have the engine revolving rather slowly. The other ratio is used for hills or for slow driving.

**709. What are the parts of the ignition system?** In the operation of a gas engine, the spark must occur at just the right time to ignite the explosive mixture. It must also occur in the proper cylinder. To accomplish this, a *timer* and *distributor* must be used. A battery system is generally used with a spark coil to produce the spark needed for ignition. A storage battery, which is charged while the engine is running, supplies the necessary current.

In Fig. 812 we have given a six-volt battery. One terminal is connected to the metal frame and to the engine; the other terminal is connected by means of the switch with the primary of an induction coil. The timer is used to "break" the circuit in the primary and thus induce a high voltage in the secondary coil. One terminal of the secondary coil is grounded and the other terminal is connected to the rotor, one part of the distributor. As this rotor makes contact with the metal segment the induced voltage is high enough to cause a spark to leap across the gap between the two terminals of the spark plug in cylinder two.

The diagram shows how each of the four cylinders will fire in turn. As the cam, A, of the timer rotates, it will break the circuit four times during one revolution. The condenser is used to fatten the spark. The fiber ring is made of insulating material, but each one of the metal segments is connected

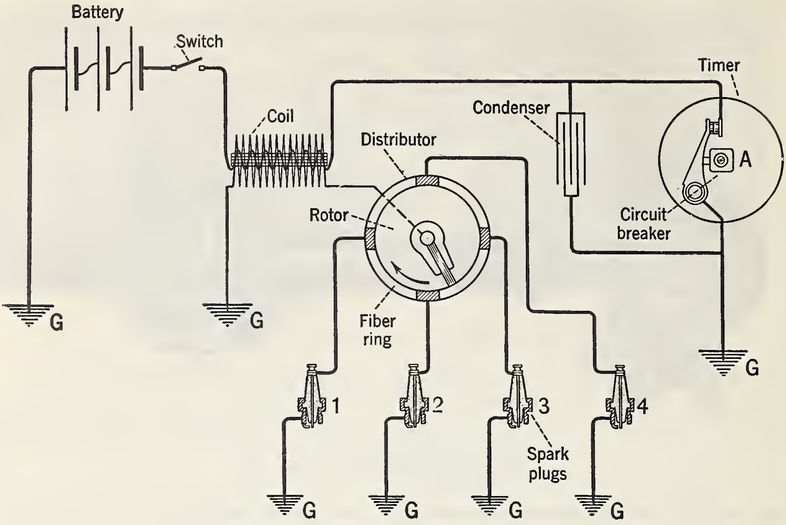
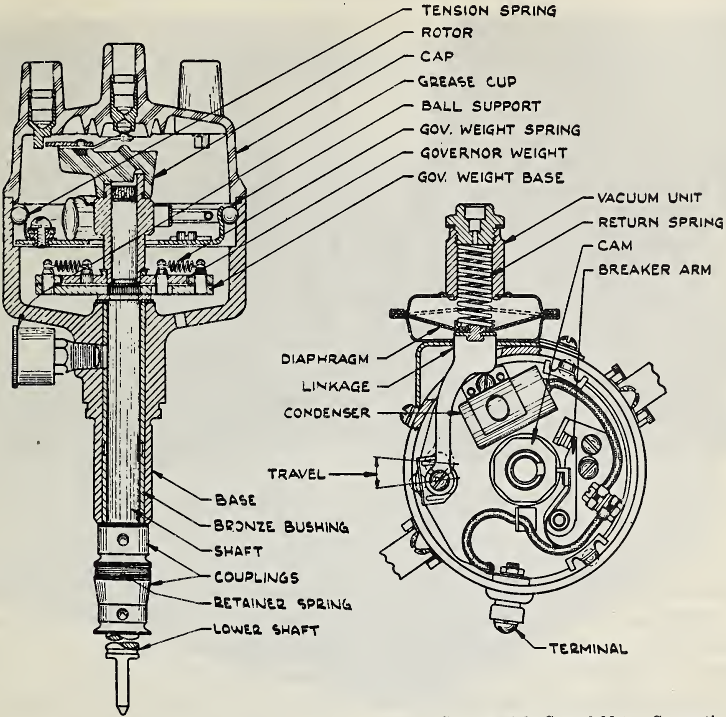


FIG. 812. Diagram showing the use of timer, coil, and distributor.

with a spark plug. As the rotor turns in the direction shown by the arrow, a spark will be produced in spark plugs numbered 2, 1, 4, and 3 in turn as it makes contact with the metal segments successively. Both the timer and distributor are geared with the engine so that the timing will be perfect. Generally, both are set on the same shaft. They are geared to rotate just half as fast as the crankshaft, since an explosion occurs once in two revolutions. (See Fig. 813.)

The combustion of the gasoline mixture is not instantaneous. When the engine is running fast, the time required for the complete combustion may be so long comparatively that the gas is not completely burned before the power stroke is completed. Then some of the unburned gas will escape through the exhaust. This difficulty is met by *advancing the spark* a few degrees so that the explosion will occur a little before the piston starts its working stroke. In order to give a fraction of a second more time for the gas to burn, it is ignited by the advanced spark before the compression stroke is quite finished. The spark is advanced by shifting the fiber ring so that it is rotated a few degrees in a direction opposite to that of the moving rotor. Thus the segments on the ring make contact with the rotor more quickly. Shifting the fiber ring in the opposite direction *retards* the spark. In the later models, the advancement and retardation of the spark are automatic.

**710. The body of the car must be strong.** The all-steel body used on the modern car is designed to give greater strength and insure greater safety. The body is hung on an "underslung" chassis to give greater stability. The windshield is made slanting to reduce the amount of light reflected into the eyes of the driver. The non-shatter glass is a safety factor. The streamlined body reduces wind resistance.


TENSION SPRING
ROTOR
CAP
GREASE CUP
BALL SUPPORT
GOV. WEIGHT SPRING
GOVERNOR WEIGHT
GOV. WEIGHT BASE
VACUUM UNIT
RETURN SPRING
CAM
BREAKER ARM
DIAPHRAGM
LINKAGE
CONDENSER
TRAVEL
BASE
BRONZE BUSHING
SHAFT
COUPLINGS
RETAINER SPRING
LOWER SHAFT
TERMINAL

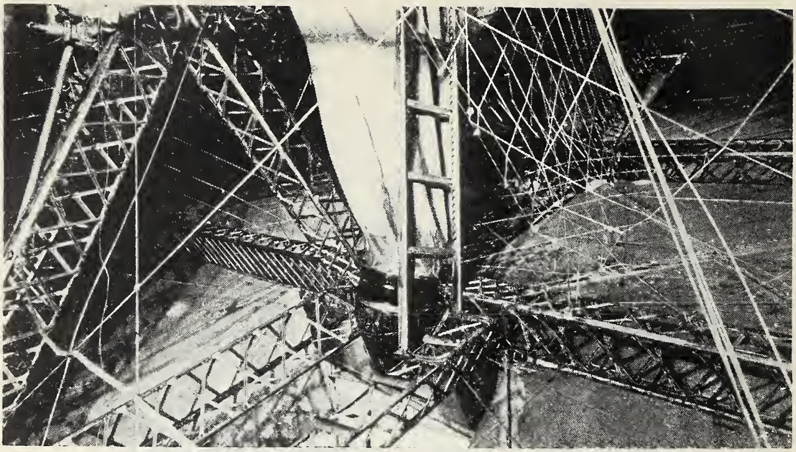
*Courtesy of the General Motors Corporation*

Fig. 813. The distributor is usually mounted on the engine.

**711. How is modern warfare changing the automobile?** With the supply of rubber cut off from the East Indies, and the demand for rubber increasing with the demands for war products, one cannot help wondering how long our automobiles can keep rolling on rubber-tired wheels. Many efforts are being made to find substitutes for rubber. Scrap rubber has been collected and reconditioned. The rabbit bush, the guayule plant, and the lowly milkweed are all being studied to learn how good a quality of rubber can be made from their saps and juices.

Chemists are busily at work making such rubber substitutes as *Buna* rubber, Thiokol, Neoprene, Ameripol, and Koroseal. Not all of these substitutes can be used in the making of tires, but some of them can be used as a substitute for the rubber in other products, thus making more natural rubber available for making tires.

Many strategic metals are needed for making the parts of both automobiles and airplanes. In many cases the demand for such use for making military planes is so great that automobile manufacturers must find substitutes. Less nickel and chromium can now be used. These metals go into the manufacture of armor plate, which ought to be hard enough and tough enough so



Official U. S. Navy Photograph

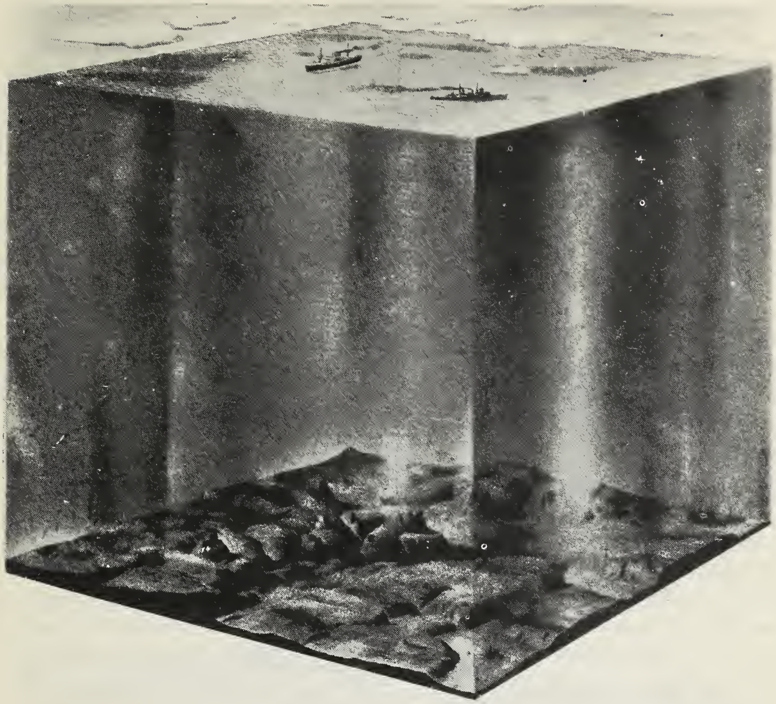
FIG. 814. Duralumin is extensively used in the construction of airplane parts and for the framework of dirigibles.

it will not be easily penetrated or shattered by projectiles.

Manganese and tungsten are two metals that must be used extensively in the making of munitions. For years the United States led the world in the production of copper, but just at present our miners cannot produce this metal fast enough. Little tin has ever been mined in the United States. It is scarce because the East Indies supply much of the tin which the world uses.

**712. Why do men make alloys?** It frequently happens that one cannot find a metal which has all of the properties that one desires. Steel, for example, is very strong, but it is about 7.8 times as dense as water. Aluminum is only 2.7 times as dense as water, but it is not nearly so strong as steel. For use in airplanes, a metal may need to be very strong and not very dense. Duralumin is an alloy containing aluminum with some manganese and some copper. It is less than half as dense as steel and almost as strong. (See Fig. 814.) In airplane construction, low density with consequent lightness is an important factor. But safety is just as important, and strength must never be sacrificed. This explains why more hydro-electric plants are extracting aluminum from its ores than ever before.

If we glance at the artist's conception of one cubic mile of sea water, as shown in Fig. 815, we must conclude that magnesium is not scarce. But an enormous plant is required to extract the magnesium from sea water, and the cost is great enough. Magnesium is only 1.75 times as dense as water, but it must be alloyed with some other metal or metals to make it strong enough for use in the parts of certain machines. The metal itself burns with an intensely hot flame, and it is used extensively in incendiary bombs. These brief glimpses of alloys and metals must convince us that war uses up our mineral resources, and that many non-war materials must be made of substitutes.



*Courtesy Dow Chemical Co.*

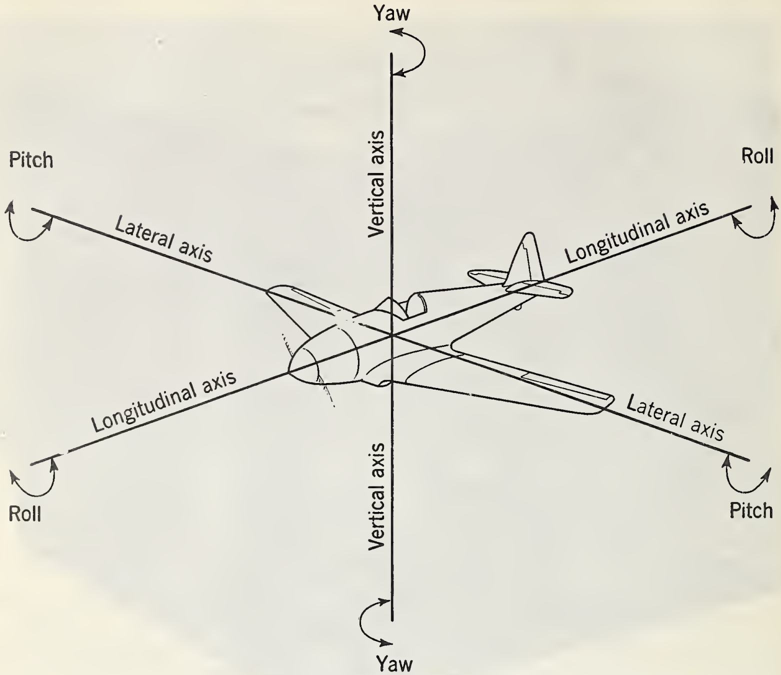
Fig. 815. An artist's conception of a cubic mile of sea water, which contains nine billion pounds of magnesium. Magnesium is now being extracted from the sea water in fairly large quantities. Do you think the present demand will continue in time of peace?

## 2. The Airplane and Its Control

**713. The airplane is a heavier-than-air machine.** A balloon or a dirigible rises because it is buoyed up by the air it displaces, and the weight of the air displaced weighs more than the balloon or dirigible and its contents. An airplane, however, is a heavier-than-air machine, and it cannot rise unless it is pushed upward by some forces which are developed by the power from the engine. As the airplane rises, it must continue to move in the direction and in the position, or *attitude*, desired.

**714. What three motions must be controlled to keep a plane steady?** Let us refer to Fig. 816. An airplane has three axes about which it can revolve. Each axis meets the other two at right angles at the center of gravity of the airplane.

The *center of gravity* in an airplane is that point from which it might be



*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

FIG. 816. Controllability about the axes of a plane is important for stability.

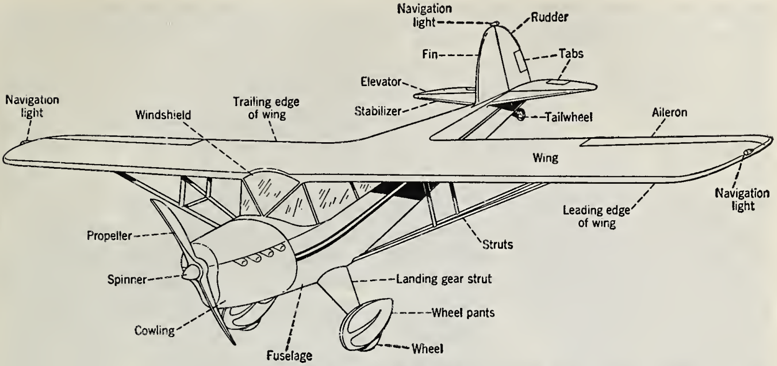
suspended in still air, and the plane would not roll, pitch, or yaw. Of course the center of gravity changes somewhat with the distribution of the load.

The *longitudinal axis* extends through the center of gravity from the front end of the airplane to the aft portion. Any movement which turns the plane about the longitudinal axis in either direction is called a *roll.* If the right wing goes down and the left wing up, there will be a roll to the right; if the left wing goes down and the right wing up, there will be a roll to the left. Stability about the longitudinal axis is increased by the stabilizer and controlled by the *ailerons* in the wings. (See Fig. 817.)

The *lateral axis* extends from the tip of one wing, through the center of gravity, to the tip of the opposite wing. Any rotation of the airplane around this axis produces *pitch.* An airplane pitches downward as its nose is pointed downward, or upward when the nose is pointed upward. Such movement is controlled by the *elevators* which are attached to the rear of the stabilizer.

The *vertical axis* extends through the center of gravity of the airplane in a perpendicular position. The turning of the airplane to the right or left about this axis is called *yawing.* Yawing is controlled by the *rudder,* which is attached to the *fin.*

**715. What forces lift an airplane?** In Section 141 we learned how a heavier-than-air airplane is partially supported by the upward component of the air


Navigation light
Rudder
Fin
Tabs
Elevator
Navigation light
Windshield
Trailing edge of wing
Stabilizer
Tailwheel
Aileron
Wing
Navigation light
Leading edge of wing
Propeller
Struts
Spinner
Landing gear strut
Wheel pants
Cowling
Wheel
Fuselage

*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

FIG. 817. This labelled drawing of a small plane shows the more important plane parts and names them. Learning these terms will help you to understand and talk the language of flying.

against which the airplane is driven. Of course the total lift force applied to the center of lift must be greater than the weight of the airplane (force of gravity), or it will not rise; the airplane will descend if such force at any time falls below the weight of the airplane. *Airfoils* cause the lift force to operate. Wings are the principal airfoils, but the stabilizer-elevator combination is another example.

In Section 142 the principle of Bernouilli was discussed. Early in the eighteenth century this law or principle was formulated by Daniel Bernouilli, a Swiss mathematician. Let us place a ping-pong ball in a small glass funnel, to the stem of which a piece of rubber tubing is attached, as shown in Fig. 818. If one blows steadily through the rubber tube, he cannot blow the ping-pong ball out of the funnel. In fact, the harder he blows, the less successful he is. Bernouilli's principle applies to both liquids and gases. Let us refer to Fig. 819 to see how Bernouilli's principle aids in supporting an airfoil or airplane wing. The air as it

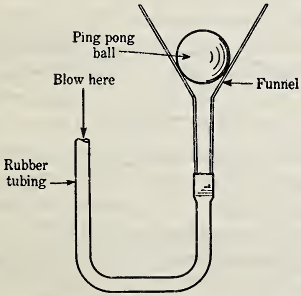

Ping pong ball
Blow here
Funnel
Rubber tubing

FIG. 818. With this apparatus one can demonstrate the principle of Bernouilli.

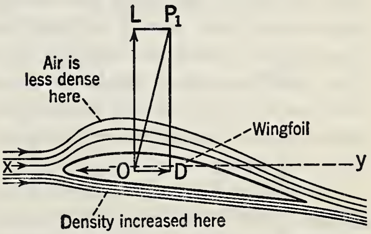

L
$P_1$
Air is less dense here
Wingfoil
X
O
D
y
Density increased here

FIG. 819. As the plane moves forward along the line $xy$, the airstream is indicated by the lines above and below the plane.

streams underneath the airfoil is retarded and the density of such air is increased. As the air flows along the top surface of the airfoil, its speed is greater than it is beneath the airfoil, and its density is decreased. Thus we have a partial vacuum above the airfoil and increased pressure beneath it. The difference in the two pressures produces what is sometimes called the "vacuum lift." A difference of only 2.5 ounces per square inch in such air pressure will produce a lift force of more than 20 lb. per square foot of wing surface. The pressure on the under surface of the airfoil contributes only one-fourth of the lift. The other three-fourths is caused by this partial vacuum on the top surface, which actually *lifts* the airfoil and the airplane.

**716. What is the principle of the airfoil?** Much experimentation has been done in wind tunnels in order to determine how the shape of an airfoil affects the lift force. Many different shapes have been tried, from the flat wing to the curved wing. Experiments show that a curved wing is better, at least for most purposes. Let us look at Fig. 820. We find that a cross section of the airfoil may be double convex, as shown in Fig. 820A. The amount of the curve of a plane is known as its *camber*. In Fig. 820B, we see that the cross section of the airfoil has one flat surface and one curved surface, the upper surface being the curved one. In Fig. 820C we have shown a cross-sectional view of an airfoil whose upper surface is convex and whose lower surface is concave.

The dotted line in Fig. 820C is the median line. The *mean* or *average camber* of an airfoil is really considered the same as the curvature of its median line. Fig. 821 shows how engineers study the characteristics of different types of airfoils by placing them in wind tunnels. As air is driven through the tunnel by means of a motor-driven fan, the wing is supported in the airstream by a wire type of balance. In such a manner the lift force and the drag force can be measured for different types of wings or airfoils.

When an airplane is in normal flight, the air will flow past the curved wing, as indicated in Fig. 819. The line of relative motion is along the path $xy$. The arrows show the relative motion of the wing to the air. The air flowing over the upward surface of the wing is deflected upward as it strikes the wing, but it is again directed downward as the wing moves on forward. The air flowing under the lower surface is slightly compressed, and also directed downward as it strikes the wing. As the air leaves the trailing edge of the wing it is given a slight downward motion, which is called the *downwash*. Since action and reaction are equal, as we learn from Newton's third law, the action which moves the air downward must have an equal and opposite reaction which produces an upward or lift force, whose center of application is at point $O$, and whose line of direction

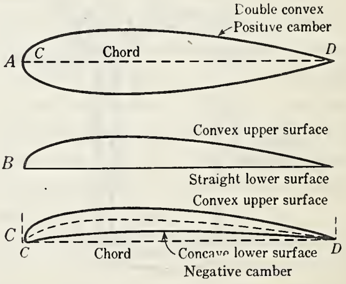
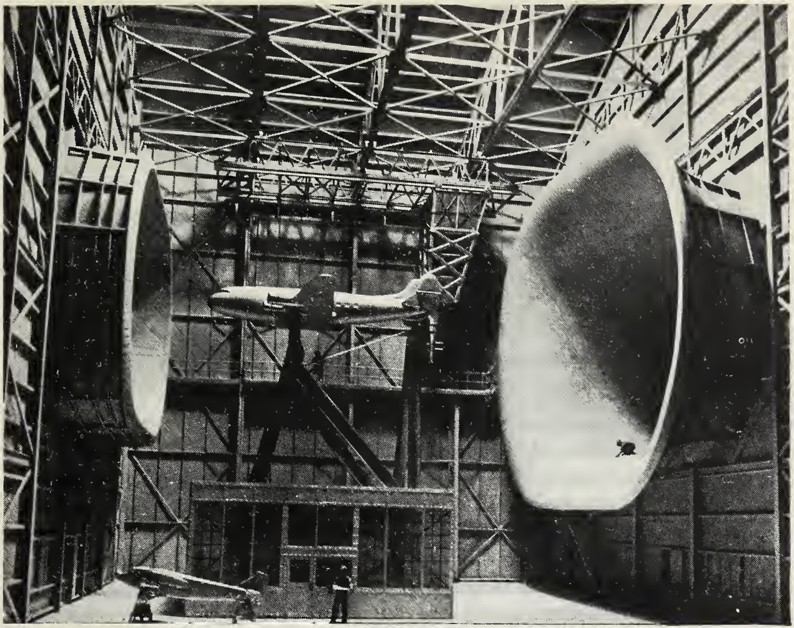


FIG. 820. Cross sections of airfoils showing three types of camber.



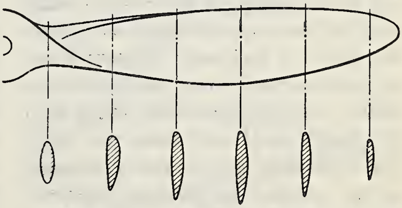
*Walt Sanders*

FIG. 821. The wind tunnel is used to test the effect of air currents on various types of planes. The size of this tunnel can be estimated by comparison with the figures of the man on the floor and the one in the tunnel.

is indicated by the line *OL*. Opposed to the traction force of the propeller there is a drag force, represented by the line *OD*. Much of this force is due to wind resistance or air resistance. The ratio of the lift force to the drag force varies with the conditions of flight and the type of the airfoils. In normal flight, the ratio is usually from fifteen to one to twenty-five to one.

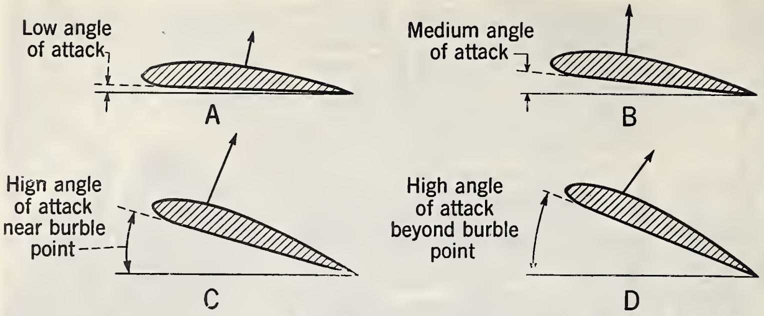
One must not forget, either, that the propeller of an airplane is also a group of airfoils. Each blade as it whirls through the air sets up the thrust force which is needed to pull the airplane through the air. To do its work effectively, the blade of the propeller must have the proper amount of camber. Fig. 822 shows how the amount of camber decreases from a point near the axis of the propeller to the tip of the propeller blade.

**717. What is meant by the angle of incidence?** A straight line from the leading edge of an airfoil to the trailing edge is called the *chord*. (See Fig.



*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

FIG. 822. The propeller is a revolving airfoil. Cross sections show that the amount of camber varies from root to tip.


Low angle of attack
A
Medium angle of attack
B
Hign angle of attack near burble point
C
High angle of attack beyond burble point
D

*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

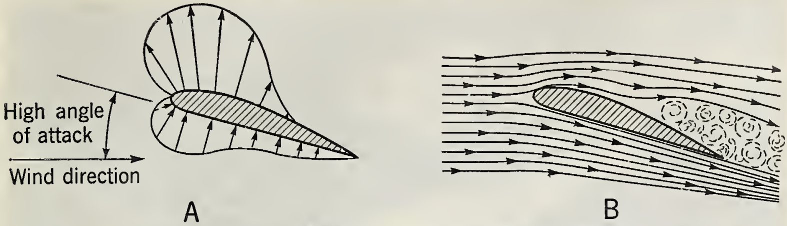
FIG. 823. How angle of attack increases to the burble point.

820A.) In an airfoil cambered like that of Fig. 820C, the surface of the airfoil does not follow the chord. The wings of an airplane are attached to the fuselage in such a manner that they make a slight angle with the longitudinal axis of the airplane. Such an angle is called the *angle of incidence*.

**718. What is the angle of attack?** In all kinds of flight, the direction of the relative wind is opposite to the motion of the airplane. In ordinary level flight the relative wind is horizontal, but when the nose is tilted downward, then the relative wind has an upward angle. In taking off, when the nose of the airplane is pointed upward, the relative wind has a downward direction. The angle between the chord of an airfoil and the direction of the relative wind is called the *angle of attack*. Of course the angle of incidence for any given airplane is fixed, since the airfoils are rigidly attached, and their angle with the longitudinal axis does not vary. The angle of attack, however, changes as the airplane ascends or descends. As an airplane is rising, the angle of attack is considered positive.

The variations possible in the angle of attack are shown in Fig. 823. The lift force of an airplane varies with the angle of attack. As a rule, it increases as the angle of attack increases. If it reaches too high an angle, known as the *critical angle*, then the airstream will no longer flow smoothly over the cambered surfaces of the airfoil, but the air will begin to *burble*, as shown in Fig. 824. The maximum angle of attack, at which burbling begins, varies with the design of the airfoil, but it is about 25° for most airplanes. At that angle at which burbling begins, the airplane reaches its stalling angle. If a pilot then wishes to regain flying speed, he must tilt the nose of the airplane downward until it gains enough speed to restore lift.

**719. What is airflow, or streamlining?** A fish is so shaped that he can glide through the water with ease. The new streamlined trains, automobiles, and airplanes show that engineers are beginning to design moving objects in such a manner that they offer less resistance to the wind. Higher speeds make such designs imperative, because the air friction increases as the square of the velocity. Formerly, many structural parts of an airplane were round in shape. It has been shown by experi-



*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

FIG. 824. The effect of a high angle of attack ($A$) on the pressures above and below the airfoil, and ($B$) on the burbling.

ment that streamlining reduces wind resistance. (See Fig. 825.) Notice the streamlining of the airfoils, the *fuselage*, the engine mountings, and the *empennage*, which includes the stabilizer and elevators, the rudder and fin, in the commercial plane of Fig. 826.

Engineers have worked out the following formula for calculating the resistance of the airflow for different shaped surfaces.

$$R = CAV^2.$$

$R$ = the resistance in pounds, when the area, $A$, is given in square feet, the velocity, $V$, is given in miles per hour, and the coefficient, $C$, is a factor which is determined by experiment. For a flat plate or surface at right angles to the air flow, as shown in Fig. 825, $C = 0.0032$; for a cylinder, the coefficient $C = 0.0025$; and for a streamlined object whose diameter is one third its elongation, $C = 0.00038$.

PROBLEM. What is the wind resistance that a board 4 in. wide and 3 ft. long encounters if it is moving with its flat side toward the wind at a velocity of 45 mi. per hr.?

*Solution.* Area = 3 ft. × $\frac{1}{3}$ ft., or 1 sq. ft. Velocity is 45 mi. per hr. Substituting in the formula, we have

$$R = 0.0032 \times 1 \times 45 \times 45.$$

Whence, $R = 6.48$ lb.

PROBLEM. What is the resistance that a streamlined piece of wood of the shape of Fig. 825 has when moving against the wind at a velocity of 45 mi. per hr., provided the piece is 3 ft. long and 4 in. in diameter?

*Solution.* Area toward wind is equal to 1 sq. ft. Velocity is 45 mi. per hr. Then,

$$R = 0.00038 \times 1 \times 45 \times 45.$$

Whence, $R = 0.97$ lb.

**720. How is an airplane stabilized and controlled?** Before an airplane can rise, it must taxi along on the ground until it gains enough speed so the lift force at a small angle of attack will

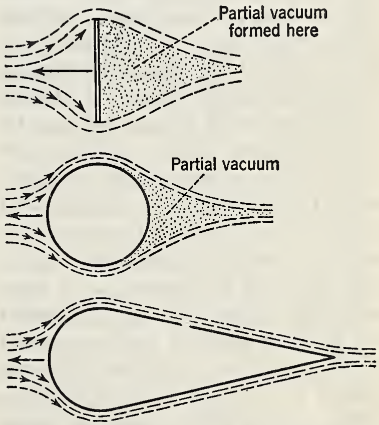
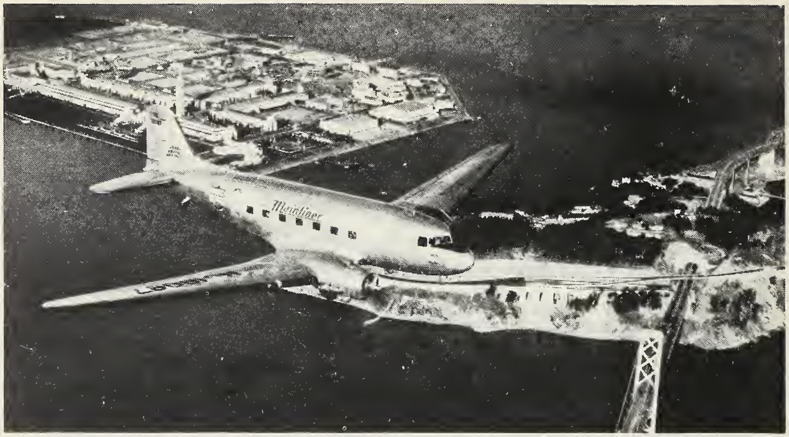


FIG. 825. The diagrams show how the air streams around ($a$) a flat board, ($b$) a cylinder, and ($c$) a streamlined object. Each one is represented as moving to the left.



Courtesy of the United Air Lines

Fig. 826. One of the latest model transport planes. Such planes make trips across the continent from daylight to dark.

become slightly greater than the weight of the plane and its load. Fig. 817 shows the various parts of a plane. As the airplane taxis along the ground, the *elevators*, which are attached to the rear edges of the *stabilizer*, are turned slightly downward to keep the nose of the plane toward the ground until the proper flying speed is reached. The center of gravity of the plane lies in the body of the plane, just beneath the wing portions. Hence, the tail of the airplane really acts as one end of a lever which may serve to tilt the nose of the plane either upward or downward, thus rotating the plane around its lateral axis. To keep the plane from being too easily rotated about its lateral axis, and to keep it on an even keel while flying, there is a horizontal *tail plane* or *stabilizer* at the rear end of the plane. The elevators, which are hinged to the rear edge of the stabilizer, can be tilted upward or downward when the pilot pulls the control stick backward or forward. When the airplane gains sufficient speed to rise, the pilot pulls the stick backward. Pulling the stick backward tilts the elevators upward and the increased force of the air against their upper surfaces pushes the tail of the airplane downward and the nose of the airplane upward. The lift force increases with the increased angle of attack, and the airplane rises from the ground. As the pilot shoves the stick forward, the elevators swing downward and the air pressure on their lower surfaces pushes the tail of the airplane upward and causes the airplane to nose downward. In such manner the upward or downward direction of the airplane is controlled by means of the elevators.

Some planes are equipped with a wheel in front of the pilot instead of a stick. Such control, which is used on large airplanes, is known as "Dep" control.

An airplane may be rotated about its vertical axis. Care must be taken to prevent the airplane from being so driven by gusts of wind from the side. At right angles to the stabilizer there is a vertical plane called the *fin*. This fin helps to increase the stability of the airplane. Hinged to the rear edge of the fin is the *rudder*. When the pilot moves the rudder to the right, the airplane swings or turns toward the right, in just the same manner that the rudder of a boat swings the bow from side to side and controls the direction of the boat.

Just as a car rounding a curve at high speed may skid outward because of centrifugal force, so an airplane rounding a curve may *skid* outward. In fact, its tendency to do so is even greater than that of the car, because its speed is so high and the air resistance against the side of the airplane is much less than the friction of the tires of a car against the pavement. To prevent such skidding when rounding curves, *ailerons* are used. Hinged to the rear edge of each wing there is a small plane called an aileron. When the pilot pushes the control stick toward the right in making a turn, the right aileron is pushed upward and the left aileron is pulled downward. Then the increased force of the air above the right wing pushes that wing downward, at the same time that the left wing is pushed upward. Both motions tend to turn the plane up into a slanting position with one wing higher than the other. With the wings in such a slanting position, the air can react in accord with Newton's third law, not only against the edge of the wings and the side of the fuselage, but it can react against a large portion of the under side of the entire airplane, wings and all, to prevent skidding.

On a certain railroad there is a very sharp curve. The rails are banked at the curve to prevent a train from being overturned by centrifugal force. The banking is great enough so that a tall freight car at rest on the curve or rounding the curve slowly might topple inward, because a plumb line dropped from its center of gravity might fall within the inner rail, as shown in Fig. 827. A fast passenger train rounding this curve must slow down to some extent to prevent the train from being overturned by centrifugal force, but a slow freight train rounding the curve may be forced to increase its speed to prevent toppling off the rails on the inside of the curve.

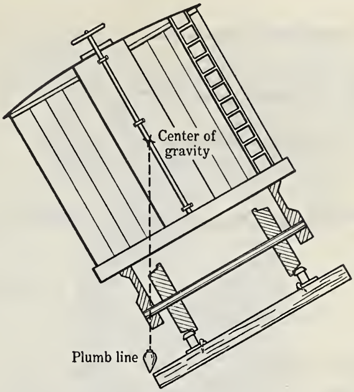
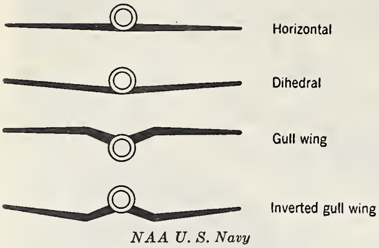


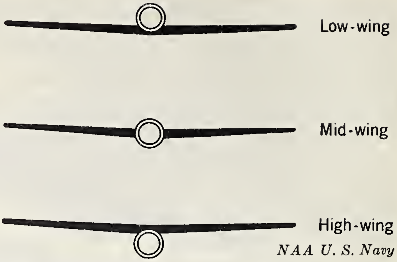
FIG. 827. How a car might topple off the inside of a steeply banked curve if rounding it too slowly.

In a similar manner, if a pilot does not bank the airplane enough in rounding a curve, the plane may skid badly from the effect of *centrifugal*, or center-fleeing, force. On the other hand, if he banks too steeply, the plane will *slip* downward from the effect of gravity. A successful pilot must learn to bank the airplane to such a degree that it will neither skid nor slip.

The wings, too, act as levers which may tend to make an airplane roll from side to side, rotating about its longitudinal axis. An upward gust of wind



*NAA U. S. Navy*



*NAA U. S. Navy*

*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

Fig. 828. Different wing shapes.

Fig. 829. Different placements of wings.

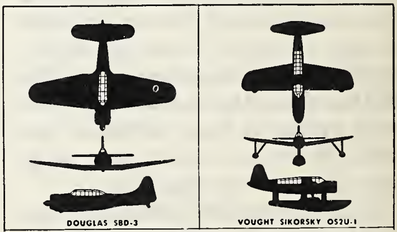
acting against the right wing, for example, will push it upward and therefore the opposite wing will go downward. Such a tendency to roll may be counteracted to some extent by elevating the tips of the wings. Such a V-shaped construction promotes stability. (See Fig. 828.)

There is a difference, too, in the portion of the fuselage to which the wings are attached. In some planes they are attached near the upper portion of the fuselage, in others near the middle, and in still other cases near the lower portion. (See Fig. 829.)

**721. How does one identify planes?** Particularly for the duration of World War II, it is important to be able to identify airplanes. It is especially desirable that even civilians shall be able to tell the difference between United States military planes and the military planes of the Axis countries. In some school shops, models are being made for such purposes. Pictures are often used, too. Since airplanes are usually seen in the air by an observer on the ground, the use of silhouettes is important. An airplane spotter may learn to recognize the silhouette of a plane as seen from beneath, as seen from its side, or as seen when the plane is approaching head-on. (See Fig. 830.)

**722. How are airplanes powered?** For wartime needs, an airplane must be able to fly at very high speeds and altitudes, and in some cases to climb very rapidly. Three things make these feats possible. (1) The use of high-test gasoline; in most cases a gasoline is used which has an octane rating of 100 or even more. To supply such gasoline is the duty of the chemist. (2) Airplane engines must be kept low in weight and must give very high horsepower. (3) A *supercharger* must be used at high altitudes where the air pressure is low, in order to keep the engine functioning properly. The latter two are problems for physicists.

**723. The Cyclone engine grows up.** Some fifteen years ago the Cyclone radial engine, which had nine cylinders, was really not a baby, because it de-



*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

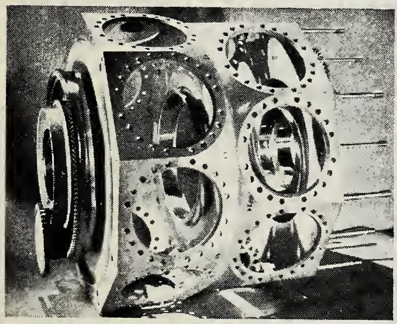
Fig. 830. Silhouettes of two common United States Army planes.

veloped 525 horsepower until a succession of improvements increased the horsepower to 1200 available for take-off. It is an air-cooled engine which is only 55 inches in diameter and weighs a trifle more than 1300 pounds.

Next the Cyclone 14-cylinder engine was designed to yield 1500 horsepower. This engine, too, has been improved until it will furnish 1700 horsepower for a take-off, and 1500 horsepower for continuous operation. It weighs just a few pounds less than a ton.

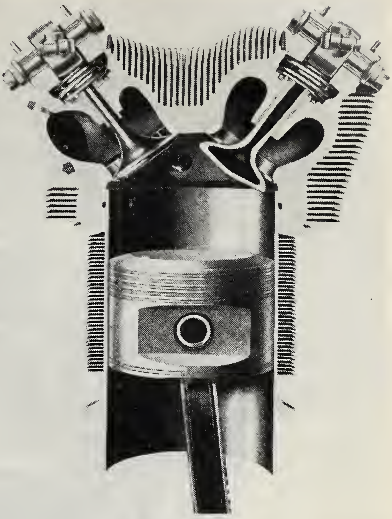
Let us take a look at the engine shown in Fig. 386. The eighteen cylinders are staggered somewhat around the crankcase. It is no larger in diameter than its predecessor. It develops well over 2000 horsepower, approximately one horsepower for one pound of weight. Can you imagine the steady flow of power that such engines develop for driving airplanes at high speeds?

Fig. 831 shows the crankcase assembly of such an engine, and Fig. 832, one of the cylinders. The cylinder head, made of aluminum, has a large number of closely spaced fins which are over 2.5 inches deep. They provide a cooling area of over 2500 square inches for each cylinder head. The heat from the engine is conducted to the fins, which radiate it to the surrounding air. The cylinder barrel is made from Nitralloy steel, and it, too, has a large number of fins which provide an additional cooling area of almost 1100 square inches. Thus each cylinder has a cooling area of more than 24 square feet. Fig. 832 shows the valves, piston, fins, and combustion chamber of one of the cylinders of this engine.



*Courtesy of Wright Aeronautical Corporation*

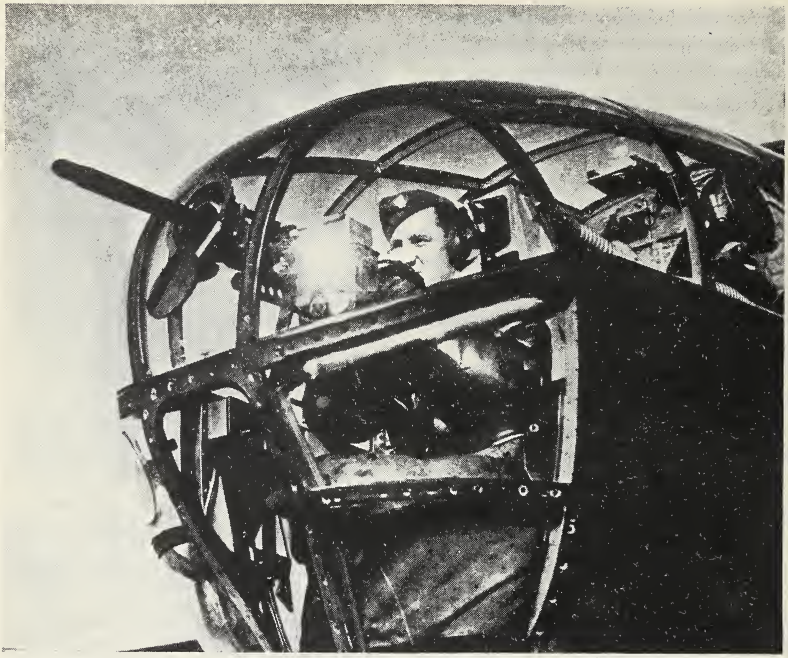
Fig. 831. Photograph of crankcase of Cyclone 18. High-tensile alloy steel is used for the engine crankcase.



*Courtesy of Wright Aeronautical Corporation*

Fig. 832. Cross section of Cyclone cylinder.

Many airplane engines are liquid-cooled Of course this creates the problem of preventing damage to the system by freezing weather or by bullets, in the case of warplanes. Damage to the liquid cooling system can render the entire engine useless. Liquid cooling systems add weight to the plane, too. But liquid cooling systems do not require the exposure of large surfaces to the air as the air cooling system does;



*Courtesy of Rohne and Haas*

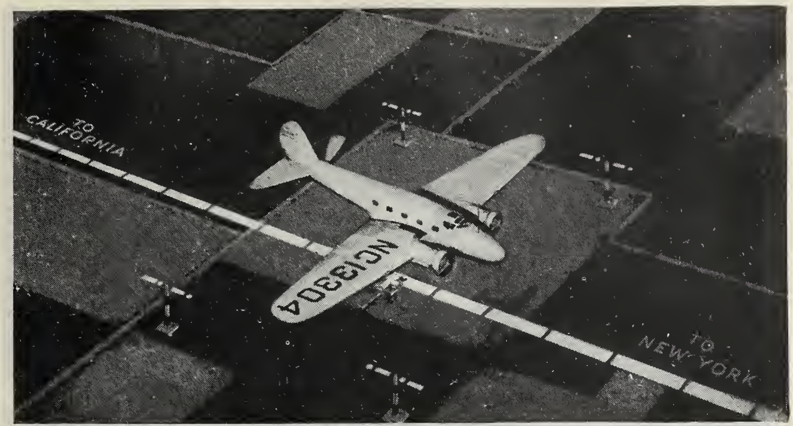
Fig. 833. Airplane with Plexiglas nosepiece. Plexiglas is so strong that a machine gun can be mounted in it.

and the smaller area exposed, the less likelihood of damage from bullets.

**724. How does the supercharger work?** The supercharger has been called the "iron lung" of the airplane engine. At an altitude of 25,000 feet, for example, the air is so rare and thin that an engine which can easily develop 1000 horsepower at sea level will develop only 400 horsepower at the higher altitude. If extra air and oxygen can be forced into the engine when the airplane is at such a high altitude, it may function at its sea-level efficiency.

The supercharger uses blades which revolve rapidly and push additional air into the engine by the use of centrifugal force. It may be driven by the engine itself or by the exhaust gases from the motor. The blades of the supercharger revolve at a high rate of speed. A machine devised by the General Electric Company is used to test the rotors of superchargers to be sure they will not fly apart under the high speeds at which they are driven. In such a machine, the rotors turn at a speed of 1000 revolutions per second. At such a speed a one-pound weight on the outer edge of the rotor exerts a centrifugal-force pull of more than 50 tons.

The two-speed supercharger attached to the Cyclone engine makes it possible for four such engines to drive the Flying Fortresses up into very high altitudes. They fly so high that the enemy is not likely to have any warning of



*Courtesy of the United Air Lines*

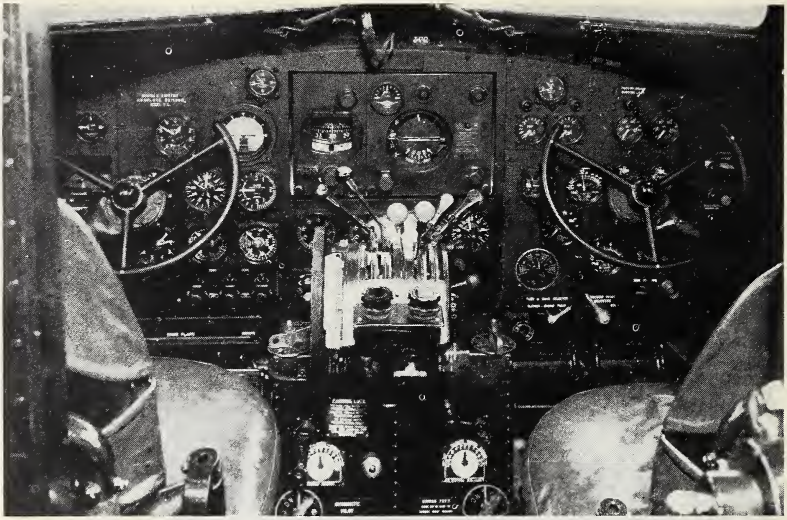
FIG. 834. The radio range or beam is used by airline pilots for "blind flying." Several hundred stations send out signals. When "on course" the pilot hears an unbroken sound. In two quadrants he hears the Morse code letter "N," and in the other two the letter "A."

their presence until he hears the scream of the falling bomb several seconds after it is released. Those seconds give the Flying Fortress time to move out of the antiaircraft gun range.

**725. What methods are used to make flying safe?** Let us mention briefly some of the methods used to reduce flying hazards. Many of the modern airplanes are almost entirely of metal, which makes them much stronger than before. They are better stabilized, too, than older airplanes. We read in our newspapers of a large number of these military planes which have been more or less riddled by bullets, with possibly much of the empennage shot away, with possibly one engine out of working order; and yet in nearly all cases they come limping home, where in a short time they can be made ready for action again. Two-, three-, and four-motored planes are safer than single-motored planes in that there is greater chance of at least one being undamaged, and one engine is usually sufficient to get the plane back to its base. Such new plastics as Plexiglas are also adding to safety in the air. (See Fig. 833.)

Landing fields have been much improved and they are better lighted at night. Many transcontinental airways have beacon lights placed a mile apart along the route.

For the duration of World War II, the publication of weather maps has been suspended. At major airports, however, weather maps are posted several times a day for the use of pilots. Different methods are used to measure the ceiling and to check visibility. By ceiling one means the altitude above which an aviator cannot see the ground below him because of low-lying clouds, mist, or fog. If the lowest clouds are at an altitude of 1500 feet, then the ceiling is said to be 1500 feet. If the mist and fog hang right at the earth's surface, the ceiling is said to be zero. By visibility one refers to the distance one can see in a horizontal direction.



*Courtesy of Transcontinental and Western Air, Inc.*

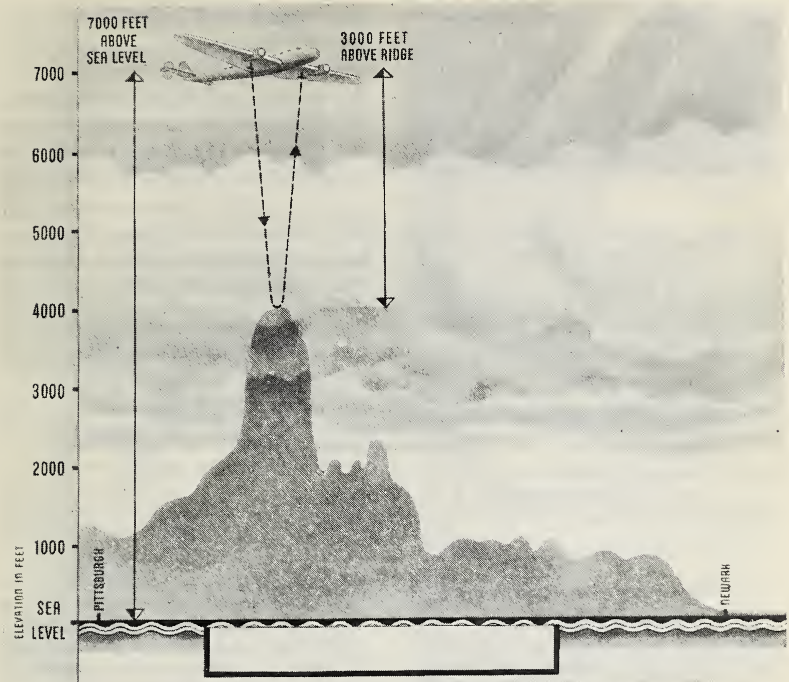
Fig. 835. The panel board contains the instruments needed for "blind flying."

But even when conditions are zero-zero, which means that there is so much fog or mist that both the ceiling and the visibility are zero, the pilot can fly using instruments alone; then he is doing what is known as *instrument flying* or "blind flying." In such a case he depends upon his radio and other intruments. If he is flying along a regular route, he may be in communication with radio stations every fifteen minutes. Fig. 834 shows the radio range or *beam* used by pilots in "blind flying." In normal times several hundred stations may send out signals. If the pilot is flying in one of the two diagonally opposite quadrants, he hears the *A* signal in Morse code; if he is flying in one of the other quadrants, he hears the *N* signal. When he is flying on his course to the station, or is "on the beam," he hears the blended *A* and *N* signals, which make a continuous hum.

Fig. 835 shows the instruments which are necessary to make instrument flying successful, but this is only a partial list of the instruments used in aviation.

One of the instruments is an *airspeed indicator*. It consists of a sensitive pressure gauge which is so graduated that it registers airspeed. It warns of approaching stalls or of steep dives. Another instrument that must be used is the *turn-and-bank indicator*. By means of this instrument the pilot can keep the airplane headed in the proper direction and can also keep his plane on an even keel. It is very important, too, to have an instrument which measures the *rate of climb*. When the pointer is at zero the pilot knows that he is neither losing nor gaining altitude.

The *tachometer* shows the number of revolutions that the engine is making per minute. The *magnetic compass* and the *altimeter* are also in the figure. These instruments are found on all well-



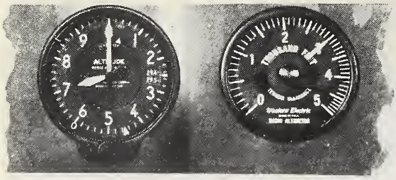
*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

FIG. 836. The terrain clearance indicator, which gives an aviator the elevation above the terrain and not merely his elevation above sea level, is an additional aid in keeping on course. The clearance can be determined by the time required for the transmitted signal to be returned to the pilot.

equipped instrument panels. Other instruments that are sometimes added include the *air-distance recorder*, a *clock* to give not only the correct time but also elapsed flying time, *drift indicator*, *fuel gauge*, *oil-pressure gauge*, *thermometer*, *voltmeter*, *ammeter*, and the *octant*.

It is really amazing how so many pilots can fly in as close a formation as they do in bombing attacks. When one sees motion pictures of scores of planes flying in formation, he wonders not only at the skill of the pilots themselves but also at the marvelous precision by which the planes are controlled. One is forced to conclude that airplane pilots must be better trained than some automobile drivers.

**726. Why is flying over mountains dangerous?** An altimeter may be set to give the height of the airplane above a particular altitude, such as sea level or the altitude of the airport at his destination. But it will not tell him the height of the terrain over which he is flying. The *terrain-clearance indicator* is a supplementary aid to keeping on course when flying over unfamiliar country. A signal may be sent downward from a small radio transmitter on one side of the airplane. The clearance is determined by the length of time before the transmitted signal is returned to the pilot, as one can easily see from the diagram, Fig. 836. Of course the reading of the altimeter is not the same as that of the terrain-clearance indicator unless the airplane is flying over land at the altitude for which the altimeter is set. (See Fig. 837.)



*From Robinson, Middleton, Rawlins, and Phillips' "Before You Fly"*

FIG. 837. Standard altimeter and terrain clearance indicator.

*How many of the following terms can you define or explain? (This group should be easy because you have had so much practice.)*

The power plant
Anti-freeze
Choke
Neutral
Intermediate speed
Synchro-mesh transmission
Ignition system
Underslung chassis
Streamlining
Tail plane
Octane number
Chassis
Drive mechanism
First speed
Third speed
Gear ratio
Advancing the spark
Camber
Elevators
Fin

## QUESTIONS

1. Is a wheel a lever? Explain.

2. With the ordinary differential, is a chain on one rear wheel a help in starting a car in the snow or on slippery streets? Explain.

3. Refer to Fig. 799 and pick out as many simple machines as you can.

4. In what different ways is it necessary to stabilize an airplane?

5. How is it possible to use the engine as a "brake" in driving down a steep hill? Is it more effective in "high" or in "low" gear?

6. What advantages does an eight-cylinder engine have over a six-cylinder engine? Has it any disadvantages?

7. What is the purpose of the "choke valve" on a car? Why is the excessive use of the "choke" wasteful?

8. Is it possible for a four-cylinder engine to furnish more power than an eight-cylinder engine? Explain.

9. Why is it easier to steer a car if the steering wheel has a large diameter?

10. Why is it necessary to bring a car to a full stop before shifting into reverse gear?

11. Explain in considerable detail how the excess heat from the engine is removed.

12. How are airplane engines cooled?

13. What is meant by the expression "flooding" as applied to the carburetor and cylinders of an engine, and why is it impossible to start a "flooded" engine?

14. Why is it economical to drive a car at moderate speed, but wasteful to drive at high speed?

15. How does increasing the diameter of the brake drums on the wheels of a car affect the braking force?

16. What is the effect of "advancing" or "retarding" the spark in the operation of a gas engine?

17. What is the purpose of the clutch and how does it operate?

18. Why should the clutch be released before trying to start a gas engine in cold weather?

19. Show how inflating a tire exemplifies (*a*) heat by friction and compression; (*b*) molecular motion; (*c*) the law of Boyle; (*d*) Pascal's law.

20. Is the energy in gasoline kinetic or potential? Discuss the transformations of energy involved in starting and running an automobile. See energy diagram, Fig. 838.

21. Will a car climb a hill more readily if

fitted with rear wheels of 30″ or of 34″ diameter?

22. How is the storage battery of an automobile kept charged? Why is it more difficult to keep a storage battery fully charged in winter than in summer?

23. Why is steering difficult if the front tires are not both inflated to the same pressure?

24. What is the purpose of synchro-mesh transmission gears?

25. Compare Figs. 839 and 840. In which case is the headlight properly focused? Explain.

26. What is wrong with the focusing of the headlights in Figs. 841 and 842?

27. What is the purpose of the elevators of an airplane? State also the purposes of the rudder, the fin, and the ailerons.

28. What advantage is there in having two different gear ratios in the differential of an automobile?

29. Why are modern automobiles and airplanes streamlined?

30. Look up the principle of the "overdrive" that is used on some modern cars. Be prepared to explain in class how it operates and why it is used.

31. Look up the subject of Diesel engines. Since they are economical to operate, why do you think that they are not used for modern pleasure cars? Find out what you can about the use of Diesels in airplanes.

32. Why is it impossible for a modern airplane to rise vertically? How does the helicopter work?

33. How is the wiring system of a modern car protected against overload?

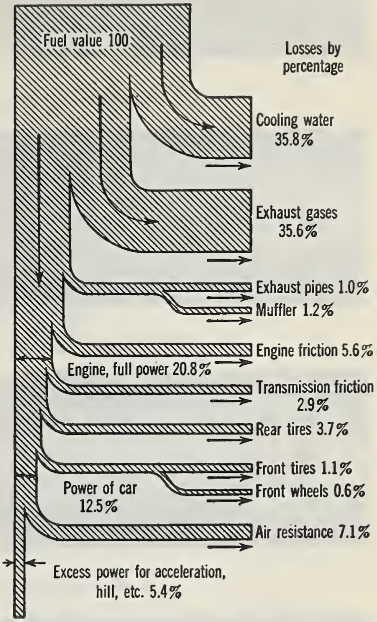

Fuel value 100
Losses by percentage
Cooling water 35.8%
Exhaust gases 35.6%
Exhaust pipes 1.0%
Muffler 1.2%
Engine friction 5.6%
Engine, full power 20.8%
Transmission friction 2.9%
Rear tires 3.7%
Front tires 1.1%
Power of car 12.5%
Front wheels 0.6%
Air resistance 7.1%
Excess power for acceleration, hill, etc. 5.4%

FIG. 838. Energy diagram for a car traveling about 40 miles per hour.

## PROBLEMS

### GROUP B

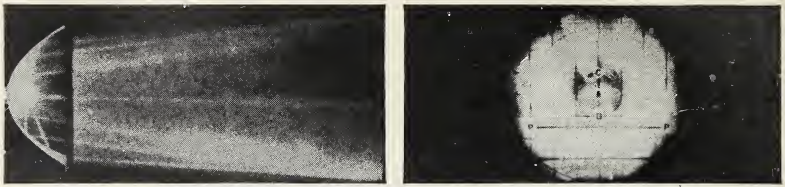
1. What is the resistance of a ten-foot cylinder, three inches in diameter, in an air stream of 150 miles per hour?

2. Calculate the resistance of the cylinder of No. 1 at an airspeed of 300 miles per hour.

3. Calculate the resistance of a streamline strut three inches in diameter and ten feet long, in an air stream of 150 miles per hour.

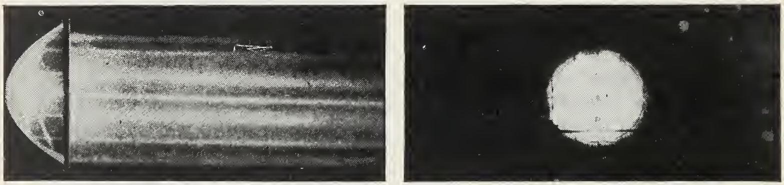
4. Calculate the total wind load on a sign board 9 feet by 12 feet in a wind having a velocity of 40 miles per hour.

5. What is the wind resistance against each square foot of a vertical windshield if the car is traveling 50 miles per hour?



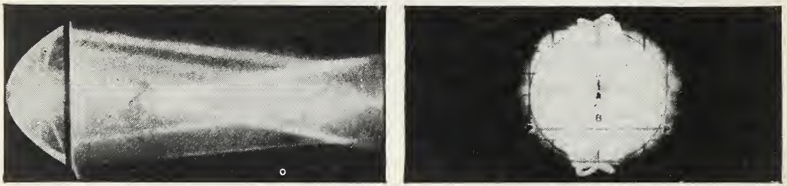
*Courtesy of the General Electric Company*

Fig. 839. Headlight, properly focused. Rays slightly divergent.



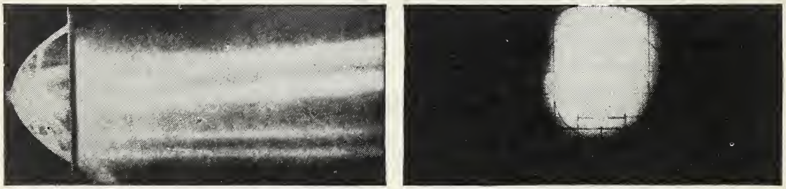
*Courtesy of the General Electric Company*

Fig. 840. When lamp is at principal focus, rays are parallel.



*Courtesy of the General Electric Company*

Fig. 841. Rays are too converging.



*Courtesy of the General Electric Company*

Fig. 842. Lamp is not centered.

# APPENDICES
and
# INDEX

# Appendix A

## FORMULAS

1. *Density.*

$$D = \frac{W}{V}.$$

$D$ is density; $W$, weight; and $V$, volume.

2. *Liquid Pressure.*

$$P = hd.$$

$P$ is pressure; $h$, the depth of the liquid; and $d$, the density.

3. *Total Force.*

$$F = ahd.$$

$a$ is the area of the surface; $h$, depth of liquid; and $d$, the density.

4. *Boyle's Law.*

$$VP = V'P'.$$

$V$ is original volume; $P$, original pressure; $V'$, new volume; and $P'$, new pressure.

5. *Accelerated Motion.*

$$V = at, \text{ or } V = gt.$$

$V$ is velocity at end of any given second; $t$, time; $a$, acceleration; and $g$, acceleration when body is freely falling.

6. *Accelerated Motion.*

$$S = \tfrac{1}{2}at^2, \text{ or } S = \tfrac{1}{2}gt^2.$$

$S$ is distance for any given number of seconds; $t$, time; $a$, acceleration; and $g$, acceleration due to gravity.

7. *Accelerated Motion.*

$$S' = \tfrac{1}{2}a(2t - 1), \text{ or } S' = \tfrac{1}{2}g(2t - 1).$$

$S'$ is the distance the body moves in any *given* second; $t$, time; $a$, acceleration; and $g$, acceleration when body is freely falling.

8. *Accelerated Motion.*

$$V = \sqrt{2aS}, \text{ or } V = \sqrt{2gS}.$$

$V$ is velocity at end of any given second; $S$, distance; $a$, acceleration; and $g$, acceleration due to gravity.

9. *Pendulum. Law of Lengths.*

$$t : t' = \sqrt{l} : \sqrt{l'}.$$

$t$ and $t'$ represent the times of vibration; $l$ and $l'$ represent the lengths of the pendulums.

10. *Pendulum.*

$$t = \pi\sqrt{\frac{l}{g}}.$$

$t$ represents time; $l$, length of pendulum; and $g$, acceleration due to gravity.

11. *Centrifugal Force.*

$$\text{C.F.} = \frac{mv^2}{gr}.$$

If $m$ represents mass in grams, $v$, velocity in centimeters, $r$, radius in cm., and $g$, acceleration due to gravity, then C.F. equals the centrifugal force in grams.

When $m$ = lb., $v$ and $r$, ft., then C.F. equals centrifugal force in pounds.

12. *Work.*

$$W = Fs.$$

$W$ represents work done; $F$, acting force; and $s$, the distance the force acts.

13. *Power.*

$$\text{H.P.} = \frac{Fs}{550t}.$$

If $F$ represents force in pounds, $s$, distance in feet, and $t$ the time in seconds, then H.P. represents horse power.

14. *Potential Energy.*

$$\text{P.E. (in gravitational units)} = mh.$$

$m$ is mass and $h$ the distance.

$$\text{P.E. (in ergs)} = mgh.$$

15. *Kinetic Energy.*

$$\text{K.E. (in ergs)} = \tfrac{1}{2}mv^2.$$

$m$ is mass in gm., and $v$ the velocity in centimeters.

16. *Work Principle.*

$$E \times d = R \times d'$$

$E$ is effort; $d$, distance effort moves; $R$, resistance; and $d'$, distance resistance moves.

17. *Lever.*

$$\text{M.A.} = \frac{EF}{RF}.$$

$EF$ is length of effort arm and $RF$ the length of the resistance arm. *M.A.* is mechanical advantage of force; the advantage of speed in machines is always the inverse ratio of the mechanical advantage of force.

18. *Pulley.*

$$En = R.$$

$E$ is effort; $R$, the resistance; and $n$, the number of strands supporting the movable block.

19. *Wheel and Axle.*

$$\text{M.A.} = \frac{C}{c} \text{ or } \frac{D}{d} \text{ or } \frac{R}{r}.$$

$C$, $D$, and $R$ represent respectively the circumference, diameter, or radius of the wheel; $c$, $d$, and $r$ represent respectively the circumference, diameter, or radius of the axle.

20. *Inclined Plane.*

$$\text{M.A.} = \frac{l}{h}.$$

$l$ represents the length of the plane and $h$ the height. (Force is applied parallel to plane.)

$$\text{M.A.} = \frac{b}{h}.$$

When force is applied parallel to the base of the plane, then $b$ represents the base and $h$ the height.

21. *Screw.*

$$\text{M.A.} = \frac{2\pi r}{d}.$$

$r$ is radius of lever upon which the effort acts, and $d$ is the interval or distance between the threads of the screw.

22. *Centigrade and Fahrenheit Scales.*

$$\frac{C}{F - 32} = \frac{5}{9}.$$

$C$ and $F$ represent Centigrade and Fahrenheit thermometer readings.

23. *Laws of Boyle and Charles.*

$$\frac{PV}{T} = \frac{P'V'}{T'}.$$

$P$, $V$, and $T$ represent original pressure, volume, and absolute temperature; $P'$, $V'$, and $T'$ represent new pressure, volume, and absolute temperature.

24. *Coefficient of Linear Expansion.*

$$K = \frac{l' - l}{l(t' - t)}.$$

$l$ represents the length before expansion; $l'$, the length after expansion; $t$, the original temperature; and $t'$, the final temperature.

25. *Heat Exchange.*

$$mst = m's't'.$$

$m$, $s$, and $t$ represent the mass, specific heat, and change of temperature in Centigrade degrees of substance losing heat; $m'$, $s'$, and $t'$ represent the mass, specific heat, and change of temperature of substance gaining heat.

26. *Wave length.*

$$v = nl.$$

$v$ is velocity of sound; $n$, the number of vibrations per second; and $l$, the wave length.

27. *Size of Object and Image.*

$$S_o : S_i = D_o : D_i.$$

$S_o$ and $S_i$ represent the size of object and image respectively; $D_o$ and $D_i$ represent the distances of object and image from the mirror or lens.

28. *Lens Formula.*

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F}.$$

$D_o$ is the object's distance; $D_i$, the image distance; and $F$, the focal length.

29. *Ohm's Law.*

$$I = \frac{E}{R}, \text{ or } I = \frac{V}{R}, \text{ or } I = \frac{P.D.}{R}.$$

$I$ is the strength of current in amperes; $R$, the resistance in ohms; $E$, the electromotive force; $V$, the voltage; and $P.D.$, the potential difference.

30. *Resistance*

$$R = \frac{Kl}{d^2}.$$

$K$ is a constant dependent upon the material; $l$ is the length in feet; and $d$ is the diameter of the conductor in mils, or thousandths of an inch.

31. *Cell Formula.*

$$I = \frac{E}{r_e + r_i}.$$

$I$ is the strength of the current; $E$, the voltage; $r_i$, the internal resistance of the cell; and $r_e$, the external resistance.

32. *Series Grouping.*

$$I = \frac{nE}{r_e + nr_i}.$$

$I$ is the strength of the current; $E$, the voltage; $r_i$, the internal resistance of a single cell; $r_e$, the total external resistance; and $n$, the number of cells.

33. *Parallel Grouping.*

$$I = \frac{E}{r_e + \frac{r_i}{n}}.$$

The letters have the same significance as in No. 32.

34. *Electric Heating.*

$$\text{Calories} = I^2R \times t \times 0.24.$$

$I$ is the strength of the current in amperes; $R$, the resistance; and $t$, the time in seconds.

35. *Shunt Resistance.*

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'}, \text{ or } R = \frac{rr'}{r + r'}.$$

$R$ represents total resistance; $r$, the resistance of one branch of the shunt; and $r'$ the resistance of the other branch.

36. *Wind Resistance.*

$$R = CAV^2.$$

$R$ represents wind resistance; $A$, the area in sq. ft.; $V$, the velocity in mi. per hr.; and $C$, a factor found by experiment.

37. *Force and Acceleration.*

$$f:W = a:g.$$

$f$ represents the force; $W$, the weight; $a$, the acceleration needed; and $g$, the acceleration due to gravity.

# *Appendix B*

## TABLE 1. — USEFUL NUMBERS

12 in. = 1 ft.
$16\frac{1}{2}$ ft. = 1 rd.
5280 ft. = 1 mi.
9 sq. ft. = 1 sq. yd.
27 cu. ft. = 1 cu. yd.
231 cu. in. = 1 gal.
1 lb. avoir. = 7000 gr.
1 oz. avoir. = 437.5 gr.
1 cu. ft. of water weighs 62.4 lb.
Circumference of a circle = $2\pi r$
Surface of sphere = $4\pi r^2$

3 ft. = 1 yd.
320 rd. = 1 mi.
144 sq. in. = 1 sq. ft.
1728 cu. in. = 1 cu. ft.
2150.4 cu. in. = 1 bu.
60 mi. per hr. = 88 ft. per sec.
1 lb. Troy = 5760 gr.
1 oz. Troy = 480 gr.
$\pi^2 = 9.86965$
Area of circle = $\pi r^2$, or $\frac{1}{4}\pi d^2$
Volume of sphere = $\frac{1}{6}\pi d^3$

## TABLE 2. — METRIC–ENGLISH EQUIVALENTS

1 in. = 2.5399 cm.
1 mi. = 1609.3 m.
1 mm. = .03937 in.
1 m. = 39.3708 in.
1 m. = 1.0936 yd.
1 sq. in. = 6.451 sq. cm.
1 lb. = 453.593 gm.
1 oz. = 28.3495 gm.

1 ft. = 30.479 cm.
1 mi. = 1.6093 km.
1 cm. = .3937 in.
1 m. = 3.2809 ft.
1 sq. cm. = 0.155 sq. in.
1 cu. in. = 16.3862 c.c.
1 kgm. = 2.2046 lb.
1 gm. = 15.432 gr.

## TABLE 3. — SPECIFIC WEIGHT OF SOLIDS

| | |
|---|---|
| Aluminum | 2.7 |
| Beeswax | 0.96 |
| Brass | 8.2–8.7 |
| Brick | 1.6–2.0 |
| Bronze | 8.7 |
| Butter | 0.94 |
| Carbon | 1.7–3.5 |
| Chestnut | 0.61 |
| Coal, anthracite | 1.26–1.8 |
| Coal, bituminous | 1.26–1.4 |
| Copper | 8.9 |
| Cork | 0.24 |
| Diamond | 3.53 |
| Elm | 0.58 |
| Glass, crown | 2.5 |
| Glass, flint | 3.0–3.6 |
| Gold | 19.3 |
| Gold, 18k | 14.88 |
| Granite | 2.65 |
| Graphite | 2.50 |
| Human body | 1.07 |
| Ice | 0.917 |
| Iron, cast | 7.1–7.6 |
| Iron, steel | 7.79 |
| Iron, wrought | 7.8–7.9 |
| Lead | 11.34 |
| Lignum vitae | 1.33 |
| Limestone | 3.18 |
| Magnesium | 1.74 |
| Maple | 0.755 |
| Marble | 2.7 |
| Oak | 0.85 |
| Paraffin | 0.824–0.94 |
| Pine | 0.46–0.55 |
| Platinum | 21.4 |
| Porcelain | 2.38 |
| Silver | 10.5 |
| Silver, sterling | 10.38 |
| Sulfur | 2.0 |
| Tin | 7.0–7.3 |
| Tungsten | 18.7 |
| Zinc | 7.1 |

## TABLE 4. — SPECIFIC WEIGHT OF LIQUIDS

| | | | |
|---|---|---|---|
| Alcohol, grain | 0.794 | Mercury | 13.56 |
| Alcohol, wood | 0.804 | Milk | 1.029 |
| Carbon bisulfide | 1.27 | Nitric acid, 68% | 1.41 |
| Carbon tetrachloride | 1.60 | Oil, castor | 0.963 |
| Chloroform | 1.50 | Oil, cottonseed | 0.924 |
| Ether | 0.72 | Oil, linseed | 0.94 |
| Gasoline | 0.68–0.71 | Oil, olive | 0.916 |
| Glycerin | 1.26 | Sulfuric acid | 1.84 |
| Hydrochloric acid | 1.20 | Turpentine | 0.87 |
| Kerosene | 0.778–0.804 | Water, sea | 1.026 |

## TABLE 5. — CAPACITY OF AIR IN GRAINS OF WATER VAPOR PER CUBIC FOOT

| Deg. F. | Grains per Cubic Foot | Deg. F. | Grains per Cubic Foot | Deg. F. | Grains per Cubic Foot | Deg. F. | Grains per Cubic Foot |
|---|---|---|---|---|---|---|---|
| 10 | .776 | 46 | 3.539 | 66 | 7.009 | 86 | 13.127 |
| 20 | 1.235 | 48 | 3.800 | 68 | 7.480 | 88 | 13.937 |
| 30 | 1.935 | 50 | 4.076 | 70 | 7.980 | 90 | 14.790 |
| 32 | 2.113 | 52 | 4.372 | 72 | 8.508 | 92 | 15.689 |
| 34 | 2.279 | 54 | 4.685 | 74 | 9.066 | 94 | 16.634 |
| 36 | 2.457 | 56 | 5.016 | 76 | 9.655 | 96 | 17.626 |
| 38 | 2.646 | 58 | 5.370 | 78 | 10.277 | 98 | 18.671 |
| 40 | 2.849 | 60 | 5.745 | 80 | 10.934 | 100 | 19.766 |
| 42 | 3.064 | 62 | 6.142 | 82 | 11.626 | 102 | 20.917 |
| 44 | 3.294 | 64 | 6.563 | 84 | 12.356 | 104 | 22.125 |

## TABLE 6. — HEAT CONSTANTS

| Name | Specific Heat | Melting Point | Boiling Point | Heat of Fusion | Heat of Vaporization |
|---|---|---|---|---|---|
| Alcohol | .65 | –130° C. | 78° C. | | 205 |
| Aluminum | .217 | 657 | 2200 | 76.8 | |
| Ammonia | | –75 | –33.5 | 108 | 295 |
| Brass | .09 | 912 | | | |
| Copper | .093 | 1065 | 2310 | 42 | |
| Glass | .198 | | | | |
| Ice | .5 | 0 | | 80 | |
| Iron | .113 | 1550 | 2450 | 28 | |
| Lead | .031 | 327 | 1525 | 5.8 | |
| Mercury | .033 | –39 | 357 | 2.8 | |
| Platinum | .0323 | 1760 | | 27.2 | |
| Silver | .056 | 961 | 1952 | 21 | |
| Steam | .48 | | | | |
| Tungsten | .0336 | 3000 | | | |
| Water | 1.00 | | 100 | | 540 |
| Zinc | .093 | 419 | 918 | 28 | |

## TABLE 7. — TENSILE STRENGTH

| Material | Pounds per Square Inch | Material | Pounds per Square Inch |
|---|---|---|---|
| Aluminum...... | 30,030–40,000 | Iron, piano wire | 357,000–390,000 |
| Brass.......... | 50,000–150,000 | Lead, drawn.... | 2600–3300 |
| Bronze wire phosphor..... | 110,000–140,000 | Platinum, drawn | 50,000 |
| Copper, drawn.. | 60,000–70,000 | Silver, drawn... | 42,000 |
| Iron, annealed.. | 50,000–60,000 | Steel, ordinary.. | 80,000–330,000 |
| Iron, hard drawn | 80,000–120,000 | Steel, maximum | 460,000 |

## TABLE 8. — VELOCITY OF SOUND IN VARIOUS MEDIA (APPROXIMATE)

| Material | Feet per Second | Material | Feet per Second |
|---|---|---|---|
| Air............. | 1,090 | Iron.................... | 16,500 |
| Aluminum....... | 16,750 | Steel................... | 16,500 |
| Brass........... | 11,500 | Water, 4° C............. | 4,590 |
| Copper.......... | 12,000 | Water, 15° C............ | 4,615 |
| Glass........... | 16,500 | Wood, along grain........ | 14,300 |
| Hydrogen........ | 4,163 | Wood, across grain....... | 12,600 |

## TABLE 9. — VAPOR PRESSURE OF WATER IN MILLIMETERS OF MERCURY

| Degrees C. | Millimeters | Degrees C. | Millimeters | Degrees C. | Millimeters |
|---|---|---|---|---|---|
| 0 | 4.5 | 23 | 20.9 | 60 | 148.9 |
| 5 | 6.5 | 24 | 22.2 | 70 | 233.3 |
| 10 | 9.1 | 25 | 23.5 | 80 | 354.7 |
| 15 | 12.7 | 26 | 25.0 | 85 | 433.1 |
| 16 | 13.5 | 27 | 26.5 | 90 | 525.4 |
| 17 | 14.4 | 28 | 28.1 | 95 | 633.7 |
| 18 | 15.3 | 29 | 29.8 | 96 | 657.7 |
| 19 | 16.3 | 30 | 31.5 | 97 | 682.1 |
| 20 | 17.3 | 35 | 41.6 | 98 | 707.3 |
| 21 | 18.5 | 40 | 54.8 | 99 | 733.2 |
| 22 | 19.6 | 50 | 92.0 | 100 | 760.0 |

## TABLE 10. — COEFFICIENT OF LINEAR EXPANSION (1° CENTIGRADE)

| | | | | | |
|---|---|---|---|---|---|
| Quartz........ | .0000005 | Iron........ | .000011 | Silver.......... | .000019 |
| Invar......... | .0000009 | Steel....... | .000013 | Tin............ | .000021 |
| Pyrex......... | .000003 | Gold....... | .000014 | Aluminum...... | .000023 |
| Glass.......... | .000009 | Copper..... | .000017 | Zinc........... | .000029 |
| Platinum...... | .000009 | Brass...... | .000019 | Lead........... | .000029 |

## TABLE 11. — DENSITY OF WATER AT VARYING TEMPERATURES

| Degrees C. | Grams per Cubic Centimeter | Degrees C. | Grams per Cubic Centimeter | Degrees C. | Grams per Cubic Centimeter |
|---|---|---|---|---|---|
| 0 | .99987 | 15 | .99913 | 60 | .98324 |
| 1 | .99993 | 20 | .99823 | 65 | .98059 |
| 2 | .99997 | 25 | .99708 | 70 | .97781 |
| 3 | .99999 | 30 | .99568 | 75 | .97489 |
| 4 | 1.00000 | 35 | .99406 | 80 | .97183 |
| 5 | .99999 | 40 | .99225 | 85 | .96865 |
| 6 | .99998 | 45 | .99025 | 90 | .96534 |
| 8 | .99987 | 50 | .98807 | 95 | .96192 |
| 10 | .99973 | 55 | .98573 | 100 | .95838 |

## TABLE 12. — NATURAL SINES AND TANGENTS

| Angle | Sine | Tangent | Angle | Sine | Tangent | Angle | Sine | Tangent |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.000 | 0.000 | 31 | 0.515 | 0.601 | 62 | 0.883 | 1.881 |
| 1 | 0.017 | 0.017 | 32 | 0.530 | 0.625 | 63 | 0.891 | 1.963 |
| 2 | 0.035 | 0.035 | 33 | 0.545 | 0.649 | 64 | 0.899 | 2.050 |
| 3 | 0.052 | 0.052 | 34 | 0.559 | 0.675 | 65 | 0.906 | 2.145 |
| 4 | 0.070 | 0.070 | 35 | 0.574 | 0.700 | 66 | 0.914 | 2.246 |
| 5 | 0.087 | 0.087 | 36 | 0.588 | 0.727 | 67 | 0.921 | 2.356 |
| 6 | 0.105 | 0.105 | 37 | 0.602 | 0.754 | 68 | 0.927 | 2.475 |
| 7 | 0.122 | 0.123 | 38 | 0.616 | 0.781 | 69 | 0.934 | 2.605 |
| 8 | 0.139 | 0.141 | 39 | 0.629 | 0.810 | 70 | 0.940 | 2.747 |
| 9 | 0.156 | 0.158 | 40 | 0.643 | 0.839 | 71 | 0.946 | 2.904 |
| 10 | 0.174 | 0.176 | 41 | 0.656 | 0.869 | 72 | 0.951 | 3.078 |
| 11 | 0.191 | 0.194 | 42 | 0.669 | 0.900 | 73 | 0.956 | 3.271 |
| 12 | 0.208 | 0.213 | 43 | 0.682 | 0.933 | 74 | 0.961 | 3.487 |
| 13 | 0.225 | 0.231 | 44 | 0.695 | 0.966 | 75 | 0.966 | 3.732 |
| 14 | 0.242 | 0.249 | 45 | 0.707 | 1.000 | 76 | 0.970 | 4.011 |
| 15 | 0.259 | 0.268 | 46 | 0.719 | 1.036 | 77 | 0.974 | 4.331 |
| 16 | 0.276 | 0.287 | 47 | 0.731 | 1.072 | 78 | 0.978 | 4.705 |
| 17 | 0.292 | 0.306 | 48 | 0.743 | 1.111 | 79 | 0.982 | 5.145 |
| 18 | 0.309 | 0.325 | 49 | 0.755 | 1.150 | 80 | 0.985 | 5.671 |
| 19 | 0.326 | 0.344 | 50 | 0.766 | 1.192 | 81 | 0.988 | 6.314 |
| 20 | 0.342 | 0.364 | 51 | 0.777 | 1.235 | 82 | 0.990 | 7.115 |
| 21 | 0.358 | 0.384 | 52 | 0.788 | 1.280 | 83 | 0.993 | 8.144 |
| 22 | 0.375 | 0.404 | 53 | 0.799 | 1.327 | 84 | 0.995 | 9.514 |
| 23 | 0.391 | 0.424 | 54 | 0.809 | 1.376 | 85 | 0.996 | 11.43 |
| 24 | 0.407 | 0.445 | 55 | 0.819 | 1.428 | 86 | 0.998 | 14.30 |
| 25 | 0.423 | 0.466 | 56 | 0.829 | 1.483 | 87 | 0.999 | 19.08 |
| 26 | 0.438 | 0.488 | 57 | 0.839 | 1.540 | 88 | 0.999 | 28.64 |
| 27 | 0.454 | 0.510 | 58 | 0.848 | 1.600 | 89 | 1.000 | 57.29 |
| 28 | 0.469 | 0.532 | 59 | 0.857 | 1.664 | 90 | 1.000 | Infinity |
| 29 | 0.485 | 0.554 | 60 | 0.866 | 1.732 | | | |
| 30 | 0.500 | 0.577 | 61 | 0.875 | 1.804 | | | |

## TABLE 13. — RELATIVE CONDUCTIVITY OF HEAT

| | | | | | |
|---|---|---|---|---|---|
| Silver | 100 | German silver | 7–8 | Magnesia | .016 |
| Copper | 92 | Mercury | 1.6 | Paper | .013 |
| Aluminum | 48 | Concrete | .22 | Sawdust | .012 |
| Zinc | 27 | Glass | .11–.23 | Wool | .010 |
| Brass | 21–28 | Sand, white | .09 | Silk | .0095 |
| Platinum | 17 | Asbestos | .04 | Felt | .0087 |
| Iron | 12–15 | Soil, dry | .033 | Air | .005 |
| Steel | 6–11.7 | Firebrick | .028 | Cotton wool | .0043 |
| Lead | 8 | Linen | .021 | | |

## TABLE 14. — INDEX OF REFRACTION

| | | | | | |
|---|---|---|---|---|---|
| Alcohol | 1.36 | Diamond | 2.47 | Olive oil | 1.47 |
| Canada balsam | 1.52 | Glass, crown | 1.52 | Opal | 1.45 |
| Carbon disulfide | 1.62 | Glass, flint | 1.54–1.94 | Water | 1.33 |
| Cotton-seed oil | 1.47 | | | | |

## TABLE 15. — VALUE OF *K*, OR SPECIFIC RESISTANCE

| | | | | | |
|---|---|---|---|---|---|
| Silver | 9.74 | Platinum | 58.8 | Manganin | 251–450 |
| Copper | 10.38 | Iron | 64.0 | Mercury | 616.5 |
| Aluminum | 17.4 | German silver | 125–196 | Nichrome | 660 |

## TABLE 16. — HYGROMETRY

| Dry Thermometer, ° F. | Difference between Dry-bulb and Wet-bulb Thermometers | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1° | 2° | 3° | 4° | 5° | 6° | 7° | 8° | 9° | 10° | 11° | 12° | 13° | 14° | 15° |
| 50 | 93 | 87 | 81 | 74 | 68 | 62 | 56 | 50 | 44 | 39 | 33 | 28 | 22 | 17 | 12 |
| 52 | 94 | 88 | 81 | 75 | 69 | 63 | 58 | 52 | 46 | 41 | 36 | 30 | 25 | 20 | 15 |
| 54 | 94 | 88 | 82 | 76 | 70 | 65 | 59 | 54 | 48 | 43 | 38 | 33 | 28 | 23 | 18 |
| 56 | 94 | 88 | 82 | 77 | 71 | 66 | 61 | 55 | 50 | 45 | 40 | 35 | 31 | 26 | 21 |
| 58 | 94 | 89 | 83 | 77 | 72 | 67 | 62 | 57 | 52 | 47 | 42 | 38 | 33 | 28 | 24 |
| 60 | 94 | 89 | 84 | 78 | 73 | 68 | 63 | 58 | 53 | 49 | 44 | 40 | 35 | 31 | 27 |
| 62 | 94 | 89 | 84 | 79 | 74 | 69 | 64 | 60 | 55 | 50 | 46 | 41 | 37 | 33 | 29 |
| 64 | 95 | 90 | 85 | 79 | 75 | 70 | 66 | 61 | 56 | 52 | 48 | 43 | 39 | 35 | 31 |
| 66 | 95 | 90 | 85 | 80 | 76 | 71 | 66 | 62 | 58 | 53 | 49 | 45 | 41 | 37 | 33 |
| 68 | 95 | 90 | 85 | 81 | 76 | 72 | 67 | 63 | 59 | 55 | 51 | 47 | 43 | 39 | 35 |
| 70 | 95 | 90 | 86 | 81 | 77 | 72 | 68 | 64 | 60 | 56 | 52 | 48 | 44 | 40 | 37 |
| 72 | 95 | 91 | 86 | 82 | 78 | 73 | 69 | 65 | 61 | 57 | 53 | 49 | 46 | 42 | 39 |
| 74 | 95 | 91 | 86 | 82 | 78 | 74 | 70 | 66 | 62 | 58 | 54 | 51 | 47 | 44 | 40 |
| 76 | 96 | 91 | 87 | 83 | 78 | 74 | 70 | 67 | 63 | 59 | 55 | 52 | 48 | 45 | 42 |
| 78 | 96 | 91 | 87 | 83 | 79 | 75 | 71 | 67 | 64 | 60 | 57 | 53 | 50 | 46 | 43 |
| 80 | 96 | 91 | 87 | 83 | 79 | 76 | 72 | 68 | 64 | 61 | 57 | 54 | 51 | 47 | 44 |
| 84 | 96 | 92 | 88 | 84 | 80 | 77 | 73 | 70 | 66 | 63 | 59 | 56 | 53 | 50 | 47 |
| 88 | 96 | 92 | 88 | 85 | 81 | 78 | 74 | 71 | 67 | 64 | 61 | 58 | 55 | 52 | 49 |
| 90 | 96 | 92 | 89 | 85 | 82 | 78 | 75 | 72 | 68 | 64 | 62 | 58 | 56 | 53 | 50 |

## TABLE 17. — PROPERTIES OF COPPER WIRE

| Gauge Number | Diameter, Mils | Ohms per 1000 Feet at 0° C. | Ohms per 1000 Feet at 20° C. | Feet per Ohm 20° C. |
|---|---|---|---|---|
| 0000 | 460 | .04516 | .04901 | 20,400 |
| 000 | 409.6 | .05695 | .06180 | 16,180 |
| 00 | 364.8 | .07181 | .07793 | 12,830 |
| 0 | 324.9 | .09055 | .09827 | 10,180 |
| 1 | 289.3 | .1142 | .1239 | 8,070 |
| 2 | 257.6 | .1440 | .1563 | 6,400 |
| 3 | 229.4 | .1816 | .1970 | 5,075 |
| 4 | 204.3 | .2289 | .2485 | 4,025 |
| 5 | 181.9 | .2887 | .3133 | 3,192 |
| 6 | 162.0 | .3640 | .3951 | 2,531 |
| 7 | 144.3 | .4590 | .4982 | 2,007 |
| 8 | 128.5 | .5988 | .6282 | 1,592 |
| 9 | 114.4 | .7299 | .7921 | 1,262 |
| 10 | 101.9 | .9203 | .9989 | 1,001 |
| 11 | 90.74 | 1.161 | 1.260 | 794.0 |
| 12 | 80.81 | 1.463 | 1.588 | 629.6 |
| 13 | 71.96 | 1.845 | 2.003 | 499.3 |
| 14 | 64.08 | 2.327 | 2.525 | 396.0 |
| 15 | 57.07 | 2.934 | 3.184 | 314.0 |
| 16 | 50.82 | 3.700 | 4.016 | 249.0 |
| 17 | 45.26 | 4.666 | 5.064 | 197.5 |
| 18 | 40.30 | 5.883 | 6.385 | 156.6 |
| 19 | 35.89 | 7.418 | 8.051 | 124.2 |
| 20 | 31.96 | 9.355 | 10.15 | 98.5 |
| 21 | 28.45 | 11.80 | 12.80 | 78.11 |
| 22 | 25.35 | 14.87 | 16.14 | 61.95 |
| 23 | 22.57 | 18.76 | 20.36 | 49.13 |
| 24 | 20.10 | 23.65 | 25.67 | 38.96 |
| 25 | 17.90 | 29.82 | 32.37 | 30.90 |
| 26 | 15.94 | 37.61 | 40.81 | 24.50 |
| 27 | 14.20 | 47.42 | 51.47 | 19.43 |
| 28 | 12.64 | 59.80 | 64.90 | 15.41 |
| 29 | 11.26 | 75.40 | 81.83 | 12.22 |
| 30 | 10.03 | 95.08 | 103.2 | 9.691 |
| 31 | 8.928 | 119.9 | 130.1 | 7.685 |
| 32 | 7.950 | 151.2 | 164.1 | 6.095 |
| 33 | 7.080 | 190.6 | 206.9 | 4.833 |
| 34 | 6.305 | 240.4 | 260.9 | 3.833 |
| 35 | 5.615 | 303.1 | 329.0 | 3.040 |
| 36 | 5.000 | 382.2 | 414.8 | 2.411 |
| 37 | 4.453 | 482.0 | 523.1 | 1.912 |
| 38 | 3.965 | 607.8 | 659.6 | 1.516 |
| 39 | 3.531 | 766.4 | 831.8 | 1.202 |
| 40 | 3.145 | 966.5 | 1049 | 0.953 |

## TABLE 18. — LENGTH OF LIGHT WAVES

| | | | |
|---|---|---|---|
| Very dark red | 0.00081 mm. | Green | 0.00052 mm. |
| Red | 0.00065 mm. | Bluish green | 0.00050 mm. |
| Reddish orange | 0.00064 mm. | Blue | 0.00047 mm. |
| Orange | 0.00060 mm. | Indigo | 0.00043 mm. |
| Yellow | 0.00058 mm. | Violet | 0.00041 mm. |
| Extreme limit of visibility | 0.00039 mm. | | |

# Index

**A battery,** 545
**Aberration,** chromatic, 395; remedies for, 346–347, 395; spherical in lenses, 395; spherical in mirrors, 346
**Absolute,** humidity, 250; temperature, 224–225; units, 112; zero, 224–225
**Absorption,** by liquids, 102; of gases, 102–103; of heat, 266–267; of light, 325; spectra, 393
**Accelerated motion,** laws of, 137–139; negatively, 139–140
**Acceleration,** defined, 136; formulas, 139, 140; laws of, 137–139; negative, 137; uniform, 136; variable, 136
**Accelerator,** 136
**Accommodation,** power of, 363
**Achromatic lenses,** 395
**Acidimeter,** 45
**Aclinic line,** 412
**Acoustics,** 294
**Action,** chemical, 206
**Adhesion,** 94
**Adsorption,** by liquids, 102; by solids, 102
**Advantage, mechanical,** 33, 178; of compound machines, 191–193; of lever, 179–180; of plane, 187; of pulley, 184–185; of screw, 189; of wheel and axle, 186
**Aërial,** 542–543
**Agent,** oxidizing, 439
**Agonic line,** 411
**Aileron,** 582, 589
**Air,** buoyancy of, 80; compressed, 69–70; density of, 49; elasticity of, 63–64; expansion of, 63–64; liquid, 248; moisture in, 250–251; pressure of, 50; standard for, 50; weight of, 49
**Air brake,** 69
**Air conditioning,** 260
**Air cooling,** 281
**Air cushion,** 84
**Air dome,** 76
**Airfoil,** 579
**Air log,** 585
**Air masses,** 58b
**Airplane,** first, 119; how stabilized, 587; how supported, 582; Hughes, 120; safety of, 593; Wright, 119
**Air pump,** 52
**Airships,** Graf Zeppelin, 81; Hindenburg, 80; Los Angeles, 80–81
**Air-speed indicator,** 594
**Alcoholometer,** 45
**Alfol,** 257
**Alpha rays,** 558
**Alpha-ray track,** 563
**Alternating current,** 499; power, 526–527; radio sets, 549
**Alternator,** 503; *versus* dynamo, 505
**Altimeter,** 56, 594
**Altitude,** measurement of, 56
**Aluminum,** extraction of, 462
**Amalgamation,** 438
**Ammeter,** 481; how used, 483
**Ammonia,** gas, 245; liquid, 245–246
**Ampere,** 423, 440
**Ampere-turns,** 453
**Amphibious equipment,** 40
**Amplification,** of audio-frequency waves, 547–548; of radio-frequency waves, 547–548
**Amplifier,** audio-frequency, 542; radio-frequency, 544
**Amplitude,** of pendulum, 143; of waves, 291
**Analogy,** water pressure, 433
**Analysis,** of light, 386–387; spectrum, 394
**Anastigmat lenses,** 368
**Anderson, Captain,** 59–60
**Anderson, Carl,** 563
**Aneroid barometer,** 54, 55
**Angle,** critical, 354; of deviation, 350; of elevation, 149; of incidence, 337; of rebound, 96; of reflection, 337; of refraction, 350; visual, 365
**Annealing,** 13
**Anode,** 458
**Antenna,** 542–543
**Anti-cyclone,** 57
**Anti-freeze solutions,** 241–242; 568
**Anti-friction metal,** 159
**Aperture,** defined, 368; effective, 368; image formed by, 342; relative, 368
**Aqueduct,** Los Angeles, 27
**Arc,** electric, 475; furnace, 478; lamp, 475; lighting, 476; mercury, 476–477
**Archimedes,** 36; portrait, 37
**Archimedes' principle,** 36–37; applications of, 40; tested, 37–38
**Aristotle,** 137
**Armature,** 409, 499; drum, 502; H-type, 500; ring, 502; telegraph, 456
**Arrhenius,** 437
**Artesian well,** 26
**Artificial ice,** 245–246
**Aspirator,** 66

**Astigmatism,** 364
**Athermanous,** 267
**Atmosphere,** height of, 60–61; moisture in, 250–251; refraction in, 354
**Atmospheric pressure,** 50
**Atom,** defined, 5, 6; structure, 5, 6, 563
**Atomic disintegration,** 560
**Atomic energy,** 560
**Atomizer,** 66–67
**Attraction,** electrical, 416; gravitational, 109–110; magnetic, 404; molecular, 94
**Audibility,** limits of, 307
**Audio-frequency waves,** 307, 542; amplified, 546, 548
**Audion tube,** 528, 545
**Audiphone,** 523
**Automatic heater control,** 217
**Automobile,** ancient, 132; axle, 577; battery, 577–578; bearings, 577; brakes, 158; camshaft, 571; carburetor, 569; clutch, liquid, 573; clutch, plate, 572; condenser, 578; cooling system, 568; cylinders, 567–568; differential, 576–577; electrical equipment, 578–579; energy diagram, 597; engine, 567–568; gear set, 574–575; headlights, 598; ignition system, 578–579; induction coil, 578; in profile, 571; modern, 132; piston, 571; power formula, 279; power plant, 567–568; sectional view. 571; spark plug, 578; synchro-mesh transmission, 575; transmission, 574; underslung, 132
**Axis,** of lens, 356–357; principal, 342; secondary, 342
**Axle,** front, 159; rear, 577

**B battery,** 545
**Babbitt,** 159
**Back E.M.F.,** 511
**Bacon, Roger,** 366
**Baffle walls,** 275
**Balance,** beam, 112, 180; Rueprecht, 112; spring, 111
**Balance wheel,** compensated, 219; elinvar, 220
**Ball bearings,** 159
**Balloons,** 80; rising, 81
**Bar,** compound, 219
**Barograph,** 55
**Barometer,** aneroid, 54; cistern, 53–54; in vacuum, 56; mercurial, 53–54; mounting of, 54; reading of, 54; self-recording, 55; uses of, 56; zero point, 54
**Baroscope,** 49
**Base,** of support, 129
**Baseball,** curves, 122
**Bathysphere,** 30
**Battery,** A, 545; B, 545; Edison, 466–467; ignition, 578–579; lead storage, 464–466; telegraph, 457; wireless, 545
**Battleship,** 40
**Beam,** 326; balance, 180
**Bearings,** Babbitted, 159; ball, 159; roller, 159; Timken, 159
**Beats,** 301, 307
**Beaufort scale,** 57, 58a
**Becquerel, Sir Henri,** 556
**Becquerel rays,** discovery of, 556–557; nature of, 558
**Bel,** 297
**Bell, Alexander Graham,** portrait, 523
**Bell, electric,** 454–455
**Bellows,** hydrostatic, 35
**Belt wheel,** 198
**Bernouilli's principle,** 122, 583
**Beta rays,** 558
**Betelgeuse,** 325
**Bicycle,** 193
**Bifocals,** 364
**Binocular vision,** 374
**Binoculars,** 376
**Biplane,** 119
**Block and tackle,** 184
**Bodies, falling,** in vacuum, 140–141; laws of, 140–141; thrown upward, 141
**Body,** of car, 567, 578
**Bohr theory,** 418
**Boiler,** fire tube, 275; water tube, 275
**Boiling,** effect of pressure on, 239; laws of, 241
**Boiling point,** effect of pressure, 239
**Bone conduction,** 524–525
**Boulder Dam,** 29
**Bourdon gauge,** 24
**Boyle, Robert,** 64
**Boyle's law,** 64; and Charles, 225–226; shown graphically, 65
**Brakes,** hydraulic, 33–34; mechanical, 158
**Breezes,** land and sea, 261
**Brick veneer,** 257
**Bridge,** George Washington, 10; Golden Gate, 11
**British thermal unit,** 207, 230
**Brittleness,** 12
**Brown, Robert,** 90
**Brownian movement,** 89
**Brushes,** 500
**Bunsen, W. H.,** 394
**Buoy,** 41
**Buoyancy,** 37–38; measurement of, 36; of gases, 78; of liquids, 36–38
**Bushnell, David,** 78
**Byrd, Rear Admiral,** 120, 550

**Cable,** power, 520; telephone, 523–524
**Caesium,** 394
**Caisson,** 70
**Calms,** Cancer and Capricorn, 262; equatorial, 262; tropical, 262
**Calorie,** defined, 229; large, 229
**Calorimeter,** 231–232
**Cam,** principle of, 198
**Camber,** 584
**Camera,** 367

**Camouflage,** 367–369
**Can,** overflow, 37
**Canal,** Panama, 27
**Candle,** standard, 330
**Candle power,** 330
**Capacity,** carrying, 471; defined, 14–15; of air, 250; of condenser, 426
**Capillarity,** defined, 99; laws of, 100; phenomena of, 100
**Capstan,** 186
**Carbon lamp,** 473
**Carburetor,** 41, 569
**Cardan, Jerome,** 367
**Carnotite,** 558
**Carrier wave,** 541
**Cartesian diver,** 77
**Cathode,** 570
**Cathode rays,** affected by magnet, 533; effects of, 532–534; fluorescent, 532; heating effects of, 532; mechanical effects of, 533; nature of, 532–533; shadows, 533
**Cell,** action in, 437; Daniell, 439; defects of, 437–438; dry, 439; Edison, 466–467; electrolytic, 458–459; gravity, 439; grouping of, 443; local action in, 437; parallel, 444; photoelectric, 553; polarization of, 438; storage, 464–466; types of, 438–439; voltaic, 434
**Celsius,** 209
**Center,** of curvature, 342, 356; of gravity, 127; of moments, 125; of oscillation, 144; of percussion, 144; optical, 357
**Centigrade,** conversion rule, 206; scale, 209
**Centimeter,** 13
**Centimeter-gram-second,** 15
**Centrifugal force,** 152; counteraction of, 152; magnitude of, 155; pump, 154
**Centrifuge,** 154
**Chadwick, James,** 563
**Chain pump,** 76
**Chains,** tire, 158
**Change,** chemical, 5; physical, 5
**Charcoal,** 102–103
**Charles, Jacques,** 223
**Charles,** law of, 223–224
**Chart,** isogonic lines, 412
**Chassis,** 567; high, 132; underslung, 132
**Chemical action,** 206
**Chimney,** 66; ejector principle, 66; stack, 261
**Chlorine,** electrolysis of, 463
**Choke,** 570
**Choke coil,** 526
**Chord,** major, 304
**Chromatic,** aberration, 395; scale, 305
**Circuit,** closed, 435; external, 435; internal, 435; open, 435; parallel, 444; series, 443; telegraph, 457; wireless, 545–546
**Circuit breaker,** 512; overload, 512; underload, 512
**Circulation,** atmospheric, 262
**Clark cell,** 440
**Cleaner,** vacuum, 68
**Clinical thermometer,** 211
**Clipper,** China, 36
**Clock,** electrical, 511; pendulum, 145, 221
**Clothes drier,** 154
**Clothing and warmth,** 256
**Clutch,** liquid, 573; mechanical, 572; use of 572
**Code, Morse,** 455
**Coefficient,** of expansion, 216; of friction, 157
**Coherer,** 545
**Cohesion,** 94
**Coil,** choke, 526; induction, 515–516; primary, 515; secondary, 515; spark, 516
**Collimator tube,** 393
**Color,** blindness, 389; of objects, 387; printing, 390; theory of, 389
**Colored films,** 392; plate, facing page 382
**Colors,** complementary, 388; primary, 388–389; spectral, 386; synthesis of, 388
**Column,** fractionating, 292
**Commutator,** 501
**Compass,** 405, 594; gyroscope, 156; radio, 549
**Compass needle,** 405
**Compensated,** balance wheel, 220–221; pendulum, 221
**Complementary,** colors, 388
**Component,** of a force, 117–121
**Composition,** of forces, 113–115; of velocities, 149
**Compound,** bar, 218; dynamo, 505; engine, 274; machines, 191–193
**Compressed air,** 69; for ventilation, 71
**Compressibility,** of gases, 64; of liquids, 64
**Compression,** heat effects of, 206; in gas engine, 278; pump, 68; uses of, 69
**Condensation,** 292
**Condenser,** commercial, 426; fixed, 547; how it works, 426; on steam engine, 274; variable, 427, 547
**Conductance,** 487
**Conduction,** and temperature sense, 256; applications of, 256; defined, 254; of electricity, 417; of gases, 255; of heat, 254–258; of liquids, 255; of solids, 254–255
**Conductivity,** and sensation, 256
**Conductometer,** 254–255
**Conductor,** charge on outside of, 421–422; of electricity, 417; shape of, 422
**Conservation,** of energy, 172; of matter, 7
**Conte di Savoia,** 156
**Continuous spectra,** 392
**Convection,** currents, 259; defined, 259; principle of, 259
**Converter,** rotary, 527
**Cooker,** pressure, 240
**Coolidge, W. D.,** 533; tube, 533
**Cooling system,** 568
**Copper oxide,** rectifier, 527
**Corliss valves,** 273
**Cornea,** 362–364

**Cornet**, 312
**Corpuscular theory**, 323
**Cottrell precipitator**, 428
**Coulomb**, 547
**Couple**, 126
**Crane**, builder's, 201
**Cream separator**, 153–154
**Critical**, angle, 354; pressure, 246; temperature, 246
**Crookes, Sir William**, portrait, 533
**Crookes**, cathode-ray discoverer, 532; radiometer, 266; tube, 532
**Crystal**, detector, 545; set, 545
**Crystallization**, 101
**Crystals**, illustrated, 101–102
**Curie, Marie Sklodowska**, portrait, 557
**Current**, alternating, 499; audio-frequency, 542; chemical effects of, 450, 458–469; continuous, 501; convection, 259; direct, 501; direction of, 450; eddy, 502; extra, 526; heating effect of, 450, 469–472; high-frequency, 540; induced, 497–507, 515–525; in loop, 499; lighting effects of, 450, 473–477; magnetic effects of, 450–458; measurement of, 483; power of, 490–491; pulsating, 543; radio-frequency, 547–548; rectified by, 527
**Curtis turbine**, 276
**Cycle**, 499
**Cyclone**, 57
**Cyclotron**, 560; uses of, 561
**Cylinder**, 272

**Dalton, John**, 389
**Daltonism**, 389
**Dam, Boulder**, 29
**Damped waves**, 540
**Daniell cell**, 439
**Davy, Sir Humphry**, 464
**Decibel**, 297
**Declination**, 411
**De Forest, Lee**, 538
**Degree**, 207–208
**De Haas**, low temperature work, 224
**Dehydrated foods**, 67
**DeLaval separator**, 154
**Delco-lighting unit**, 468
**Demagnetization**, 405
**Density**, defined, 15; formula, 16; related to specific weight, 42; specific, 42
**Derrick**, 186, 201–202
**Descartes**, experiment, 77
**Detectors**, 542–543
**Deuteron**, 560
**Deviation**, angle of, 350
**Dew point**, 251
**Diagrams**, conventional, 436
**Diaphragm**, 359
**Diathermanous**, 267
**Diatonic scale**, 304
**Dictating machine**, 313
**Die**, for drawing wire, 11
**Dielectric**, 426
**Diesel engine**, 283
**Difference**, of potential, 424
**Differential**, 576
**Diffraction**, 396; grating, 396
**Diffusion**, by reflection, 338; by transmission, 339; of gases, 91; of liquids, 92; of solids, 93; promotion of, 338
**Dimmer**, 526
**Dip**, magnetic, 412
**Dipping needle**, 412
**Direct current**, 501
**Dirigible**, 81
**Disappearing gun**, 151
**Discharge**, electrical, 531
**Discontinuous spectra**, 392
**Discord**, 306
**Dispersion**, 386
**Distance**, judgment of, 365–366; of object and image, 347, 359
**Distillation**, 241; destructive, 242; fractional, 241
**Distinct vision**, 369, 370
**Distributor**, 577–578
**Diver, Cartesian**, 77
**Diver's helmet**, 71
**Diving**, bell, 70; suit, 70
**Doldrums**, 262
**Dolland**, 395
**Doppler's principle**, 298–299
**Draft**, 261
**Drift**, 121
**Drive**, mechanism, 572; wheel, 275
**Drum-wound armature**, 502
**Dry**, cell, 439; dock, 40; farming, 100; ice, 219
**Ductility**, 11
**Duration**, of vision, 376
**Dynamo**, alternating-current, 500; compound, 504; direct-current, 501; eight-pole, 505–506; self-exciting, 504; series, 504; shunt, 504; simple, 499; *versus* alternator, 505
**Dynamo rule**, 498
**Dyne**, 112

**Ear**, 288–289
**Ear phones**, 546
**Ear trumpet**, 297
**Earth**, a magnet, 410–413; inductive action of, 413
**Ebullition**, 238
**Eccentric**, 198
**Echoes**, 292; how used, 292
**Eclipse**, 327
**Economizer**, 276
**Economy**, of light, 332–333
**Eddy currents**, 502
**Edison, Thomas A.**, portrait, 473
**Edison**, cell, 466–467; effect, 544; electric bulb, 473; shaft at Menlo Park, 473
**Effects of current**, chemical, 458–469; heat-

ing, 469–472; lighting, 473–477; magnetic, 450–458
**Efficiency**, 178; of car, 586; of gas engine, 281; of human body, 271; of locomotive, 271; of simple machines, 191; of steam engine, 271; of transformer, 518; of water wheels, 195
**Effort**, 178
**Einstein, Albert**, portrait, 135; views, 324
**Ejector**, 66
**Elastic constant**, 95
**Elastic limit**, 95
**Elasticity**, defined, 94; kinds, 94; measurement of, 94; perfect, 95
**Electric**, ammeter, 481; arc, 475; battery, 464–467; bell, 454; charge, 421; circuit, 435; circuit breaker, 512; curling iron, 470; current, 450–477, 499–503; discharge in vacuum, 531; flatiron, 470; furnace, 478; fuse, 472; galvanometer, 481–482; generator, 500–504; grill, 470; hair drier, 470; heater, 470; heating pad, 470; lamps, 473–477; light, 473–477; meter, 490; motor, 507–511; power, 490; rectifier, 527; telegraph, 457; telephone, 521–523; transformer, 517–518; transmission, 518–519; units, 440; waffle iron, 470; welding, 471; whirl, 429
**Electric clock**, 511
**Electric locomotive**, 509
**Electricity**, 4; and magnetism, 451; by friction, 415; in motion, 433–434; negative, 416; positive, 416; theory of, 417
**Electrification**, by contact, 419; by induction, 420
**Electrode**, 458
**Electrolysis**, laws of, 464; of chlorine, 463; of copper salts, 463; of water, 458–459
**Electrolyte**, 458–459
**Electrolytic cell**, 458–459
**Electro-magnet**, 452; how made, 453; magnet rule, 453; polarity of, 453; strength of, 453; uses of, 453–455
**Electro-metallurgy**, 462
**Electro-motive force**, 527
**Electron**, 6, 418–419, 533, 560
**Electronics**, 88
**Electron theory**, 418
**Electrophorus**, 427
**Electro-plating**, 460
**Electroscope**, charging by induction, 420–421; metal-foil, 416; pith-ball, 416
**Electro-typing**, 460–461
**Elevator**, 34
**Elevators**, 588
**Elinvar**, 220
**E.M.F.**, back in motor, 511; induced, 497; strength of, 511
**Emulsion**, 101
**Energy**, 4; atomic, 560; conservation of, 172; diagram, 271, 597; kinds of, 170–171; measurement of, 171; mechanical, 206; transformation of, 172
**Engine**, Diesel, 282; external combustion, 272–275; gas, 278–279; internal combustion, 278–279; semi-Diesel, 282; steam, 272–275; turbine, 276–277
**English system**, 13
**Equator**, magnetic, 412
**Equilibrant**, 115; of parallel forces, 126
**Equilibrium**, 128; neutral, 130; stable, 129; unstable, 130
**Erg**, 167
**Escapement wheel**, 145
**Ether**, 266, 323
**Ethylene glycol**, 569
**Evaporation**, cooling effect of, 244; laws of, 237–239; of liquids, 92; of solids, 93
**Exciter**, 503
**Exhaust pump**, 65
**Exhausted tubes**, 50
**Expansibility**, of gases, 63
**Expansion**, and density, 223; coefficient of, 216; force of, 226; of gases, 223; of liquids, 220; of solids, 215–218; problems dealing with, 217; unusual expansion of water, 234
**Experiment**, Pascal's, 51; Torricelli's, 51
**Extension**, 7
**Extinguisher**, 78
**Extra current**, 526
**Eye**, accommodation, 363; defects of, 363; forms images, 363; structure of, 362; *versus* camera, 367

**Factor**, of safety, 97; power, 525
**Fahrenheit scale**, 209
**Fall of potential**, 485–486
**Farad**, 426, 547
**Faraday, Michael**, portrait, 497
**Faraday**, 421, 464, 496; bag, 421; laws of, 464
**Farsightedness**, 364; remedy, 364
**Fatigue**, of metals, 10; retinal, 390
**Feed water heater**, 276
**Field**, magnetic, 500; motor, 507–510; revolving, 510; types of winding, 504
**Field magnet**, 499; energized, 503
**Filament circuit**, 545
**Film**, 377–379
**Fin**, 582
**Fireless**, gas range, 257
**Fires**, fighting, 26
**Fizeau, Armand**, 353
**Flame**, manometric, 315
**Fleming**, 544; valve, 544
**Floating objects**, 38–40
**Floodlighting**, 380
**Flotation**, laws of, 39; principle of, 38
**Fluid drive**, 573
**Fluid friction**, 158
**Fluids**, mobile, 6; viscous, 6
**Fluorescence**, 557, 559
**Fluorescent lamps**, 382–383
**Fluoroscope**, 537
**Flywheel**, 571

**Focal length,** of lens, 357; of mirror, 342
**Focus,** principal, 342, 357
**Foley, A. L.,** 294–295
**Foot-candle,** 331; meter, 332
**Foot-pound,** 165
**Foot-poundal,** 167
**Foot-pound-second system,** 15
**Force,** centrifugal, 152; centripetal, 152; defined, 109; gravitational, 109; how measured, 111; moment of, 125; on bottom, 22; on side, 23; total and construction work, 26; units of, 110
**Force pump,** 75
**Forces,** composition of, 114–115; equilibrant of, 115; molecular, 97; parallel, 125; parallelogram of, 112–114; represented graphically, 112; resolution of, 116–117; resultant of, 113
**Forearm,** 181
**Forecasts,** long-range, 58b, 60
**Formulas,** grouped in Appendix A
**Four-cycle engine,** 278–279
**Fractional distillation,** 241
**Frame,** box-type, 570; X-braced, 570
**Franklin, Benjamin,** portrait of, 424; experiment, 424; theory of electricity, 417
**Fraunhofer lines,** 392–393
**Free liquid,** shape of, 99
**Freezing,** evolves heat, 236; expansion during, 233–234; mixtures, 236; point, 208
**Frequency,** audio, 307, 542; defined, 292; in alternating current, 499, 500; in wave formula, 292; radio, 307, 542
**Friction,** advantages of, 156; coefficient of, 157; defined, 156; disadvantages of, 156; fluid, 158; increased by, 158; laws of, 156–157; produces heat, 270; reduced by, 158–159; rolling, 159; sliding, 156–157
**Fronts,** cold and warm, 58b
**Fundamental,** 307–308
**Furnace,** arc, 478; electric, 478; hot-air, 263; hot-water, 263; pipeless, 263; resistance, 478; steam, 264; vapor, 264
**Fuse wires,** 472
**Fuses,** types, 472
**Fusion,** defined, 233; heat of, 235

**Galileo Galilei,** portrait, 137; experiments, 50, 138–140, 143, 207
**Galvani, Luigi,** 434
**Galvanometer,** movable-coil, 482; movable-needle, 482; reflecting, 482
**Galvanoscope,** 487
**Gamma rays,** 558
**Gas engine,** 278–279
**Gases,** 6; compressibility of, 63–64; convection by, 259; diffusion of, 90; electrical discharges through, 530–531; exert pressure, 90; expansion of, 63, 90; liquefaction of, 244; mechanics of, 63–91; molecular motions of, 90–91; sound transmission by, 288; spectra of, 392
**Gas-filled lamp,** 474
**Gas law,** 226
**Gas manometer,** 82
**Gas mask,** 103
**Gas meter,** 82–83
**Gauge,** Bourdon, 24; mercury, closed, 82; mercury, open, 24; steam, 25; tire, 82
**Gauss,** 407
**Gay-Lussac, Louis,** 223
**Gear ratio,** 576
**Gears,** bicycle, 193; synchro-mesh, 575; to vary speed, 192; transmission, 573–575
**Gearshift,** 195, 574
**Gear wheels,** 192
**Geissler tubes,** 531
**Generator,** Alexanderson, 541; audion tube, 541; automobile, 578; commercial, 500–505
**George Washington,** 158
**Gilbert, Sir William,** 411, 415
**Glasses,** opera, 374–375
**Glycerine,** 568–569
**Governor,** 153
**Grade,** 187
**Gram,** 13, 15
**Gram-centimeter,** 167
**Gram of force,** 112
**Gramme ring,** 502–504
**Grand Coulee,** 172
**Graph,** direct proportion, 22; inverse proportion, 65; temperature, 212
**Grating,** diffraction, 396
**Gravitation,** 109; law of, 110
**Gravitational units,** 112
**Gravity,** acceleration due to, 137–140; center of, 127; specific, 42
**Grid,** 545
**Grid circuit,** 546
**Grid leak,** 546
**Ground,** 542–543
**Grouping of cells,** 443–444; formulas for, 443–444
**Gun,** disappearing, 151
**Gyroscope,** 156; compass, 156

**Hall, Charles Martin,** 462; process, 462
**Hall rule,** 498
**Hammer,** 182
**Hammond organ,** 311
**Hardness,** 12
**Harmonic,** 308
**Harmony,** 306
**Headlights,** 346, 597
**Heat,** 4; and solution, 236; and temperature, 207; and work, 270–271; capacity, 230; converted into work, 270–271; defined, 205; distribution of, 254–266; during condensation, 244; effects of, 215–249; effects shown graphically, 249; induction heating, 520; latent, 235, 242–243; mechanical equivalent of, 270–271; nature of, 205; of fusion, 235;

of solidification, 236; of vaporization, 242–243; sources of, 205–206; specific, 230; theory of, 205; transparency, 267; units of, 229, 230
**Heating effects of current,** 469–470; applications, 470
**Heating systems,** compared, 264–265; hot-air, 263; hot-water, 263; pipeless, 263; steam, 264; vapor, 264
**Helium,** 80, 559
**Helix,** 452
**Helmholtz, Augustus von,** 317
**Hemispheres,** Magdeburg, 52
**Henry, Joseph,** portrait, 525; electro-magnet, 453; law of, 103
**Henry,** electrical unit, 547
**Hertz, Heinrich,** portrait, 538; wave theory, 324
**High-tension line,** 518
**Hindenburg,** 80
**Hoist,** hydraulic, 34
**Holland,** 78
**Holland Tunnel,** 71
**Hooke's law,** 96
**Horsepower,** 168; of automobiles, 279
**Hot-air heating,** 263
**Hot-water heating,** 263
**Hot-water tank,** 265
**Hughes, Howard,** 120; his plane, 120
**Humidity,** absolute, 250; and evaporation, 238–239; defined, 250; relative, 250; relative and temperature, 250–251
**Hurricane,** 56
**Huygens,** 266, 323
**Hydraulic,** brakes, 33–34; elevator, 33–34; hoist, 34; jack, 34; press, 12, 33
**Hydro-electric plant,** 197
**Hydrogen,** 80
**Hydrometer,** 45
**Hydroplane,** 120
**Hydrostatic bellows,** 35
**Hygrodeik,** 251

**Ice,** artificial, 245; on airplanes, 251
**Iceberg,** 38
**Iconoscope,** 556
**Ideal dynamo,** 499
**Ignition system,** 577–578
**Illumination,** 325; diffusion, 379; direct, 379; flood, 381; floor, 380–381; fluorescent, 381; indirect, 379–380; law of, 330; neon, 383; semi-indirect, 379–380
**Illusions,** optical, 367–368
**Images,** by concave lenses, 359; by convex lenses, 357–358; by concave mirrors, 343–345; by convex mirrors, 345; by plane mirrors, 340; by small openings, 340; compared with object, 347, 359; kinds of, 339; real, 339; virtual, 339
**Immiscible liquids,** 101
**Impact,** 146–147, 206
**Impedance,** 526
**Impenetrability,** 8
**Incandescent lamps,** 473–475
**Incidence,** angle of, 96, 337, 350
**Inclination,** magnetic, 412–413
**Inclined plane,** 187
**Incompressibility,** of liquids, 64
**Indestructibility,** 7
**Index, of refraction,** 352; uses of, 352
**Indicator,** drift, 595; terrain clearance, 56, 595; turn and bank, 594
**Induced current,** 496–497, 499, 500; E.M.F., 496–499
**Inductance,** 547
**Inductance coils,** 526, 547
**Induction,** by moving conductor, 496; charging by, 420–421; earth's, 412–413; electrical, 496, 515; heating by, 520; magnetic, 406
**Induction coil,** 516; uses of, 516
**Induction heating,** 520
**Induction machine,** 428
**Induction motor,** 509–510
**Inertia,** 8, 9, 145
**Infra-red photography,** 391
**Input,** 179, 180
**Instruments,** bells and plates, 312; membranes, 313; musical, 310–314; optical, 362–382; stringed, 310; wind, 312
**Insulator,** electrical, 417; heat, 256–258; petticoat, 518
**Intensity,** of light, 330; of sound, 296
**Interference,** of light, 395; of sound, 300
**Internal-combustion engine,** 278; comparison of, 281; cooling of, 280; Diesel type, 282; four-stroke, 278; horsepower of, 279; multi-cylindered, 279; Wright Cyclone, 281; United Air lines, 281
**Ion,** 418–419
**Ionization,** air molecules, 563–564; in solution, 437
**Iris,** 362
**Isobars,** 58
**Isoclinic lines,** 412
**Isogonic lines,** 411; chart of, 412
**Isotherms,** 58

**Jackscrew,** 190
**Janssen,** 370
**Joliot, Irène,** portrait, 557
**Joule, James Prescott,** 167, 270; laws of, 469, 470
**Joule,** unit of work, 167

**Kaleidoscope,** 341
**Kelvin, Lord** (Sir William Thomson), portrait, 205
**Key,** 456
**Kilocycle,** 540
**Kilogram,** 15
**Kilogram-meter,** 167
**Kilometer,** 13
**Kilowatt,** 168; hour, 490

**Kinescope,** 556
**Kinetic theory,** 89
**Kirchhoff,** 394
**Knife switch,** 472
**Koenig,** 315

**Lactometer,** 46
**Lag curve,** 525–526
**Lake,** 78
**Lake Placid,** bob-sled, 153
**Lamp,** arc, 475; carbon, 473; development of, 474; gas-filled, 474; incandescent, 473–475; mercury vapor, 476; neon, 383; tungsten, 474; ultraviolet, 477; vapor, 476; wiring for, 475
**Lampshades,** 378–380
**Land breezes,** 262
**Lantern,** optical, 375–376
**Latent heat,** 235, 242–243
**Lawn,** mower, 117; sprinkler, 150
**Lawrence,** 561
**Laws,** of accelerated motion, 138–139; of boiling, 241; of Boyle, 64; of capillarity, 100; of Charles, 223–224; of conservation of energy, 7, 173; of conservation of matter, 7; of cooling, 267; of electrolysis, 464; of evaporation, 238; of falling bodies, 140–141; of flotation, 39; of friction, 157; of Gay-Lussac, 223–224; of gravitation, 110; of heat exchange, 231; of Henry, 103; of Hooke, 96; of illumination, 330; of intensity, 333; of Joule, 469, 470; of Lenz, 498; of liquid pressure, 21; of machines, 178; of magnets, 404; of motion, 145; of Ohm, 440; of Pascal, 31; of pendulum, 143; of radiation, 267; of rebound, 95; of reflection, 337; of refraction, 353; of resistance, 441–442; of strings, 309, 310
**Lead cell,** storage, action in, 465; commercial, 465–466
**Lead-in wires,** 218
**Leaning Tower of Pisa,** 137
**Left-hand rule,** 509
**Length,** units of, 13
**Lens,** achromatic, 395; anastigmat, 368–369; converging, 355; diverging, 356; flat, 365; formula, 359; how affect light, 356; how form images, 357; meniscus, 365; rectilinear, 368–369
**Lenz's law,** 498
**Leslie's cube,** 266–267
**Letter press,** 190, 201
**Lever,** classes of, 180; defined, 179; first-class, 180; how affect by their own weight, 181; mechanical advantage of, 179, 180; second-class, 180; third-class, 181
**Leyden jar,** 426
**Life preserver,** 39
**Lift,** 121
**Lifting,** force, 80; magnet, 454
**Lift pump,** 75
**Light,** 4; amount needed, 332; analysis of, 386; color of, 386; diffraction of, 396; diffusion of, 324–325; dispersion of, 386; focusing of, 342; intensity of, 330; interference of, 395; measurement of, 330–332; monochromatic, 386; nature of, 323; polarization of, 396–397; polychromatic, 386; rays, beams, and pencils, 326; reflection of, 337; refraction of, 350–353; sources of, 324–325; theories of, 323; velocity of, 328
**Lighting,** arc, 475; diffusion, 379; direct, 379; flood, 381; floor, 380–381; fluorescent, 381; indirect, 379–380; neon, 383; semi-indirect, 379–380
**Lightning,** artificial, 425; identical with electricity, 424
**Lightning rods,** 424–425
**Light valve,** 378
**Light waves,** compared to sound waves, 324
**Lincoln Tunnel,** 72
**Lindbergh, Colonel Charles,** 120
**Linde,** 248
**Line wires,** 518
**Lines,** aclinic, 412; agonic, 411; isobars, 58; isoclinic, 412; isogonic, 411; isothermal, 58; of force, 406–407, 451–452
**Liquefaction,** 233; of air, 248; of gases, 246–248
**Liquid air,** 248
**Liquid clutch,** 573
**Liquid films,** 97; elasticity of, 98
**Liquids,** 6; buoyancy of, 36–38; conductivity of, 255; diffusion of, 92; evaporation of, 92, 237–238; expansion of, 220; incompressibility of, 64; mechanics of, 19–48; molecular motions of, 92–93; osmosis of, 92–93; pumps, 75–76; sound transmitted by, 288
**Liter,** 13, 15
**Loading coils,** 524
**Local action,** 458; remedy for, 458
**Lockyer, Sir Norman,** 394
**Locomotive,** electric, 510; illustrated, 275
**Locomotive diagram,** 275
**Lodestone,** 403
**Longitudinal waves,** 291
**Los Angeles,** 80
**Loudness,** how affected, 296; how measured, 297; special conditions, 297
**Loud-speaker,** 550; electro-dynamic, 550
**Lubricant,** 160
**Lumen,** 332
**Luminous objects,** 325

**Machine,** compound, 191; defined, 177; driven, 197–198; driving, 197–198; efficiency of, 191; electrical, 428; inclined plane, 187; laws of, 178; lever, 179–181; mechanical advantage of, 178; pulley, 183–185; purposes, 177; screw, 189, 190; self-exciting, 504; simple, 178; water turbine, 196; wedge, 188; wheel and axle, 185–186

**Magdeburg,** hemispheres, 52–53
**Magnet,** artificial, 403; electro-, 452–454; field, 499; horseshoe, 409; Mayer's floating, 407; natural, 403; permanent, 405; temporary, 405
**Magnetic,** attraction, 404; declination, 411; dip, 412; field, 407–408; induction, 406; lines of force, 406–407; materials, 403–404; permeability, 405; poles, 404; repulsion, 404; retentivity, 405
**Magnetism,** and electricity, 428; how destroyed, 405–406; how produced, 403; induced, 406; residual, 504; terrestrial, 410–411; theory of, 409; theory *versus* facts, 410
**Magnetite,** 403
**Magneto,** 500
**Magnifier,** 369
**Magnifying power,** of binoculars, 375; of lens, 370; of microscope, 371; of telescope, 371
**Major chord,** 304; triad, 304
**Malleability,** 12
**Manometer,** closed, 82; open, 24
**Manometric flame,** 315
**Marconi, Guglielmo,** 538
**Mass,** 7
**Materials,** magnetic, 403; non-magnetic, 404; strength of, 96
**Matter,** changes in, 6, 7; conservation of, 7; defined, 4; impenetrability of, 8; indestructibility of, 7; kinetic theory of, 89; measurement of, 13–15; nature of, 5; properties of, 7–10; special properties of, 10–13; states of, 6; structure of, 5
**Maximum thermometer,** 211
**Maximum-and-minimum thermometer,** 211; self-recording, 212
**Maxwell, James Clerk-,** portrait, 324; theory, 538
**Maxwell,** 407
**Measurement,** English, 13; metric, 13
**Mechanical advantage,** 33, 178
**Mechanics,** of gases, 63–91; of liquids, 19–48
**Megaphone,** 297
**Melting point,** 208; effect of pressure on, 234–235
**Membranes,** 313
**Meniscus,** 99; lenses, 364–365
**Mercurial barometer,** 53–54
**Mercury-vapor lamp,** 476
**Meridian,** magnetic, 411
**Metals,** extraction of, 461; plating of, 460
**Meter,** 13–14
**Metric system,** 13
**Metric tables,** 13–14
**Michelson, Albert,** portrait, 325; work on velocity of light, 329
**Micro-farad,** 426, 547
**Micro-henry,** 547
**Micrometer,** 191
**Microphone,** 542, 549
**Microscope,** 370
**Mil,** 442; circular, 442
**Mile-long tube,** 329
**Milhenry,** 547
**Millibar,** 58a, 58b
**Millikan, Robert,** portrait, 540
**Mineral wool,** 257
**Mirror,** applications, 345; concave, 343; convex, 345; curved, 342; formulas, 347, 359; images in, 343–345; kinds, 343–345; parabolic, 347
**Miscible liquids,** 101
**Mixtures,** methods of, 231
**Mobile,** 6
**Modulator,** 541–542
**Moisture,** 250–251
**Molecular motions,** 89–91
**Molecule,** 5; in motion, 89–91
**Moment,** of force, 125
**Moments,** center of, 125
**Momentum,** 146
**Monsoon,** 262
**Moon,** eclipses of, 327
**Morse, Samuel F. B.,** portrait, 456
**Morse code,** 456
**Morse telegraph,** 456
**Motion,** accelerated, 137; curvilinear, 135; defined, 135; kinds of, 135–137; laws of, 137–139; picture film, 377; pictures, 376–377; reciprocating, 272; retarded, 137; rotary and translatory, 126; uniform, 136; variable, 136
**Motion pictures,** films, 379; how projected, 376; principle of, 376; sound film, 377
**Motions,** molecular, 89–91
**Motor,** A.C., 509–510; back E.M.F., 511; direct-current, 507–509; induction, 509–510; rule, 509; series, 509; shunt, 509; starting, 511; streetcar, 509; Wright Whirlwind, 119
**Motor generator,** 527
**Motor rule,** 509
**Music,** 306
**Musical instruments,** 310–314; scale, 304–306

**Nature,** of solids, liquids, and gases, 94
**Nearsightedness,** 363; remedy for, 363–364
**Needle,** dipping, 412–413
**Neon,** 383
**Neon lamp,** 383
**Neon tubes,** illustration of, 383
**Neutral,** 573
**Neutron,** 6, 418, 563
**Newton, Sir Isaac,** portrait, 110
**Newton,** 145, 323; laws of cooling, 267
**Nichrome,** 470
**Node,** 308
**Noise,** 306
**Normal,** 337

**Normandie**, 40
**North magnetic pole**, 411

**Octant**, 595
**Octave**, 304–305
**Oersted, Hans Christian**, portrait of, 451; experiment, 450
**Ohm, Georg Simon**, portrait, 441; law, 440; for A.C., 526
**Ohm**, 423, 440
**Oil engine**, 283
**Onnes, Kamerlingh**, 224
**Opaque objects**, 326
**Opera glasses**, 374
**Ophthalmoscope**, 346
**Optical illusions**, 367–368
**Optical instruments**, 362–380
**Optical lantern**, 375
**Ore crane**, 149
**Organ, Hammond**, 311
**Organ pipes**, 310–311
**Oscillation**, center of, 144
**Oscillograph**, 534
**Oscillograph curves**, 534
**Osmosis**, 91–92
**Osmotic pressure**, 93
**Otto von Guericke**, 53, 415
**Output**, 179, 180
**Overload**, 471
**Overload circuit breaker**, 512
**Overtones**, 308

**Panama Canal**, locks, 27
**Parabolic mirror**, 347
**Parallel**, forces, 125; grouping, 444
**Parallelogram**, of forces, 114–115
**Parson's turbine**, 276–277
**Pascal, Blaise**, portrait, 52; experiment, 51
**Pasteur, Louis**, 370
**Pelton wheel**, 196
**Pencils**, converging and diverging, 326–327
**Pendulum**, compensated, 220; compound, 143–144; defined, 143; laws of, 143; simple, 143; uses of, 144
**Pentode tube**, 550
**Penumbra**, 327
**Percussion**, center of, 144
**Period**, 143
**Periscope**, 355
**Permalloy**, 405
**Permanent magnets**, 405
**Permeability**, 408
**Perpetual motion**, 173
**Petroleum**, 242
**Phonodeik**, 316
**Phonograph**, 313
**Photo-electric cell**, 378, 553
**Photography**, 392; color film, 392; infra-red, 392
**Photometer**, Bunsen, 333; Joly, 333; photo-electric, 333; spherical, 334
**Photometry**, 330
**Photomicrograph**, 315
**Photon**, 324
**Physics**, defined, 3, 4, 7
**Pictures**, motion, 376; film, 377–379
**Pigments**, mixing, 390
**Pinhole camera**, 342
**Pipeless furnace**, 263
**Pipes**, organ, 310–311; overtones in, 311
**Pipette**, 62
**Pisa**, leaning tower, illustrated, 137
**Piston**, 272
**Pitch**, 298; American Federation of Musicians, 306; concert, 306; international, 306; of a screw, 190
**Pitchblende**, 556
**Planck, Max**, 324
**Plane**, inclined, 187; mechanical advantage of, 187
**Plate**, circuit, 545; negative, 435; of crystals, 101–102; positive, 435
**Pneumatic**, caisson, 70; despatch, 70; tires, 67
**Point**, boiling, 208; fixed, 209; freezing, 208
**Points**, effect of, 422
**Polariscope**, 397
**Polarity**, 404; laws of, 404; of an electro-magnet, 453
**Polarization**, defined, 438; of light, 396–397; prevented, 439; remedied, 439
**Polaroid**, 399
**Poles**, consequent, 410; earth's, 410–411; magnetic, 404; of electro-magnet, 453
**Porosity**, 8
**Positron**, 563
**Pound**, 15
**Poundal**, 112
**Pound of force**, 112
**Power**, alternating current, 526–527; defined, 167; electric, 490; factor, 525; measured, 168; transmission of, 197–198, 518; units of, 168
**Power cable**, 520
**Power plant**, Grand Coulee, 172; Tennessee Valley, 519
**Precipitation**, 251
**Press, hydraulic**, 12, 33
**Pressure**, absolute, 82; applied to liquids, 31; atmospheric, 50; critical, 246; defined, 19; depends on, 19–21; electrical, 423; formula for, 19–20; independent of, 20–21; laws of, 21; liquid, 19–24; measurement of, 24; of air, 50; on confined liquids, 31; osmotic, 93; related to density, 65; related to depth, 19; standard, 49
**Pressure cooker**, 240
**Pressure gauge**, 82
**Prevost's theory**, 231
**Primary**, cell, 434; colors, 388–389; coil, 515; pigments, 390; rainbow, 394
**Principle**, Archimedes', 36: Bernouilli's, 122,

583; Doppler's, 298–299; of convection, 259; of flotation, 38; of moments, 125
**Printing,** three-color, 390; illustrated, Frontispiece
**Prism,** right-angle, 355
**Projectile,** fired at an angle, 148; path of, 148
**Projecting lantern,** 375
**Projector,** 375–377; floodlight, 382
**Proofplane,** 419
**Properties of matter,** general, 7–10; special, 10–13
**Proportion,** direct, 22; inverse, 65
**Proton,** 6, 418–419, 560
**Psychrometer,** 250–251
**Pulley,** combinations of, 184–185; defined, 183; differential, 194; mechanical advantage of, 184–185; types of, 184–185
**Pump,** air, compression, 68; air, exhaust, 65–66; aspirating, 66; centrifugal, 154; chain, 76; force, 75; lift, 75; suction, 74
**Pupil,** 363
**Pycnometer,** 44
**Pyrex,** 217–218

**Quality,** 307–308
**Quantum theory,** 324

**Radar,** 88, 564
**Radiation,** 254, 266; good radiators, 266; laws of, 267
**Radio,** 537–557; compass, 549
**Radio-activity,** 556; artificial, 563
**Radio-frequency,** 307, 546; amplification, 548; waves, 542
**Radiograph,** 536
**Radiometer,** 266
**Radio waves,** audio-frequency, 542; continuous, 541; damped, 540; frequency of, 540; generated by, 540; modulated, 541; radio-frequency, 542; reception of, 542–543; transmission of, 541
**Radium,** bromide, 556; discovery of, 556–557; disintegration of, 559; period of half decay, 560; properties of, 557; rays, 558
**Radium A, B, C, D, E, and F,** 560
**Radium dials,** 557
**Radon,** 560
**Rainbow,** primary, 394; secondary, 395
**Ramp,** 187
**Range,** 149; electric, 257; gas, 257
**Range finder,** 366
**Rarefaction,** 292
**Ray,** 326
**Rayon,** 155
**Rays,** alpha, 558; Becquerel, 557–558; beta, 558; cathode, 532–533; cosmic, 539; effects of cathode, 532–533; fluorescent effect, 532; gamma, 558; heating effects, 532; magnetic effects, 533; Millikan, 539; nature of, 532–533, 539, 558; shadow effect, 533; through glass, 533–534; ultra-violet, 477
**Reactance,** 526
**Reaction,** 150
**Real images,** 339
**Rebound,** angle of, 95; law of, 95
**Receiver,** telephone, 522–523
**Receiving set,** 545
**Reciprocating motion,** 199
**Recorder,** electro-magnetic, 314
**Records,** electrically cut, 314
**Rectifiers,** 527
**Rectilinear lenses,** 368
**Refining metals,** 463
**Reflection,** angle of, 357; diffused, 338; multiple, 341; of light, 337–355; regular, 337; total, 355
**Reflector,** 346
**Refraction,** angle of, 350; applications of, 352–353; atmospheric, 354; cause of, 351; index of, 352; laws of, 353; through glass plate, 353; through prism, 354
**Refractometer,** 352
**Refrigeration,** electric, 246; gas, 246; mechanical, 245–247
**Refrigerator,** 247, 259
**Regelation,** 234
**Relative humidity,** 250; effect on comfort, 251; effect on temperature, 250
**Relay,** 457
**Repeater,** 523
**Repulsion,** electrical, 416; magnetic, 404
**Resistance,** ammeter, 481; coils, 481; computed by, 442; formula, 442; furnace, 478; internal and external, 442–443; laws of, 442; measurement of, 442; substitution, 491; temperature effect on, 441; unit of, 423; voltmeter, 482; voltmeter-ammeter method, 491; Wheatstone bridge, 491–492
**Resistance box,** 481
**Resistance thermometer,** 210
**Resolution of forces,** 116–117
**Resonance,** 300
**Resonant length,** best, 300–301
**Resonator,** 300; Helmholtz, 317
**Resultant,** defined, 113; of forces at any angle, 114; of forces in line, 113
**Retarded motion,** 139
**Retentivity,** 405
**Retina,** 362
**Retinal fatigue,** 390
**Reverse,** 575
**Rheostat,** 484
**Right-hand rule,** 451
**Ring-wound armature,** 502–504
**Riveter,** 71
**Robot bombs,** 151
**Rock drills,** 71
**Rocket airplanes and bombs,** 151
**Rock wool,** 257
**Roemer,** 328
**Roentgen, Wilhelm Conrad,** portrait, 535; rays, 535

**Roller bearings,** 159
**Rolling mills,** 12
**Roof truss,** 118
**Rotary converter,** 527
**Rotary sprinkler,** 151
**Rotor,** 276–277, 507–509; squirrel cage, 510
**Rubidium,** 394
**Rudder,** 582
**Rule,** dynamo, 498; Hall, 498; left-hand, 509; motor, 509; right-hand, 451
**Rutherford, Ernest,** 558

**Saccharimeter,** 397
**Safety factor,** 97
**Sailboat,** 117–118
**Saxophone,** 312
**Scale,** chromatic, 305; diatonic, 304; tempered, 305
**Scales,** Centigrade, 209; conversion, 209; Fahrenheit, 209
**Science,** defined, 3
**Screen grid tube,** 550
**Screw,** defined, 189
**Sea breeze,** 261
**Seaplane,** 36, 120
**Searchlight,** 346
**Second,** 15
**Secondary,** cell, 464–466; coil, 515
**Segment,** 308
**Self-exciting dynamo,** 504
**Self-induction,** 524
**Self-starter,** 509, 571
**Semi-conductor,** 417
**Semi-Diesel engine,** 282
**Semitone,** 305
**Series,** grouping, 443; wiring, 486
**Shadow,** 327
**Shaft,** counter-, 573–575; crank, 571; drive, 573–575
**Shape,** free liquid, 99; of conductor, 422; of liquid surface, 99
**Shears,** tailor's, 180; tinner's, 180
**Sheave,** 184
**Short circuit,** 471–472
**Shovel,** steam, 194
**Shunt circuit,** 483; division of current in, 488; resistance of, 489
**Sine,** 352
**Singing flame,** 307
**Sink,** kitchen, 84
**Siphon,** 76; aspirating, 84; intermittent, 84
**Siren,** 298
**Size,** judgment of, 365; object and image, 347, 359
**Skiagraph,** 536
**Slip rings,** 500
**Solar spectrum,** 386
**Solenoid,** 452
**Solidification,** 233; volume changes, 233–234
**Solids,** conductivity of, electrical, 417; conductivity of, thermal, 254–255; density of, 15; diffusion of, 93; evaporation of, 93; expansion of, 215–218; molecular motion of, 93; spectra, 392; transmitters of sound, 288
**Solubility,** 101; effect of temperature on, 101
**Solute,** 101
**Solution,** nature of, 101; of liquids, 101; of solids, 100
**Solvent,** 100
**Sonometer,** 308
**Sound,** characteristics of, 296; defined, 289; duration of, 294; insulation against, 289; intensity of, 296; interference of, 301; loudness of, 296–297; measurement of, 297; media for transmission, 287–288; nature of, 287–288; pitch of, 298; photographed, 295; quality of, 307–308; reflection of, 293–295; source of, 287; transmission of, 287–288; velocity of, 290
**Sounder,** 456
**Sounding,** 294
**Sound-picture theater,** 380
**Sound pictures,** how made, 377–378
**Sound ranging,** 291
**Sound reflector,** 297
**Sound waves,** illustrated, 315–318; photographed, 294–295; relation between length and frequency, 292–293; shown graphically, 315–318
**South magnetic pole,** 411
**Spark,** advanced, 578; retarded, 578
**Spark coil,** 516
**Sparking voltage,** 531
**Speaking tube,** 297
**Specific,** density, 42; gravity, 42; heat, 230; volume, 222; weight, 42
**Specific-gravity bottle,** 44
**Spectra,** absorptive, 393; continuous, 392; discontinuous, 393
**Spectral chart,** *opposite* page 398
**Spectroscope,** 394
**Spectrum analysis,** 394; solar, 393
**Speed,** forward, 574; reverse, 575
**Speed counter,** 200
**Speedometer,** 154
**Spherometer,** 190–191
**Spinthariscope,** 558
**Spirit of St. Louis,** 120
**Squirrel-cage motor,** 509–510
**Stability,** 129
**Stabilizer,** 156, 581
**Stack,** 261
**Standard,** candle, 330; cell, 440; pitch, 306; pressure, 63; set, 545; temperature, 63
**Standpipe,** 25, 28
**Starting,** resistance for motors, 511–512; torque, 509
**States of matter,** 6
**Static electricity,** 415–430

**Stator**, for generator, 506–509; for turbine, 276–277
**Steam**, boiler, 275; engine, 272–275; heat, 264; latent heat of, 242–243; shovel, 118, 194; turbine, 276–277
**Stereopticon**, 375
**Sterilizer**, ultra-violet, 477
**Stethoscope**, 297
**Stevens, Captain**, 59–60
**Still**, 242–243
**Storage cell**, 464–466
**Strain**, 94–95
**Stratosphere**, 59–60
**Streamlining**, 586; formula, 587
**Streetcar**, 509; motor, 509
**Strength**, of E.M.F., 499; of materials, 96
**Stress**, 94–95
**Strings**, laws of, 309
**Sublimation**, 239
**Submarine**, 78; awash, 80; diagram of, 79
**Suction pump**, 74
**Supercooled water**, 251
**Supersonics**, 286
**Surface tension**, 97
**Switch**, knife, 472; three-way, 494
**Sympathetic vibrations**, 299
**Synchro-mesh transmission**, 575
**Synchronism**, 511
**Synthesis**, 388

**Tables**, Appendix B; and map symbols, 58a
**Tail plane**, 581
**Tank**, army, 111
**Telegraph**, 455–457; connection, 457
**Telephone**, cable, 523–524; simple, 521; trans-Atlantic, 552–553; transmitter, 522
**Telescope**, astronomical, 371; field, 375; Lick, 372; Mount Wilson, 374; reflecting, 371; refracting, 371; terrestrial, 374
**Teletype**, 458
**Television**, 553–555; picture, 556; reception, 554; transmission, 554
**Temperature**, absolute, 224; and sensation, 207; Centigrade, 209; critical, 246; Fahrenheit, 209; standard, 63
**Tempered scale**, 305
**Tempering**, 12
**Tenacity**, 10
**Tennessee Valley Authority**, 519
**Tensile strength**, 10–11
**Tension**, surface, 97
**Terms**, electrical, 436
**Terrain-clearance indicator**, 595
**Terrella**, 411
**Thales**, 415
**Theory**, corpuscular, 323; electromagnetic, 324; kinetic, 89; of color, 389; of electricity, 418; of magnetism, 409; of voltaic cell, 437; wave, 323–324
**Thermal capacity**, 230
**Thermo-couple**, 210
**Thermograph**, 212; records, 212
**Thermometer**, air, 207; Centigrade, 208; clinical, 210–211; construction of, 208; conversion of, 209–210; differential, 266–267; Fahrenheit, 208; gas, 210; graduation of, 208; limitations of, 210; maximum, 211; maximum-and-minimum, 212; mercury, 208; metallic, 219; minimum, 211; platinum resistance, 210; self-registering, 212; special, 210–212; thermo-couple, 210; wet-and-dry bulb, 251
**Thermos bottle**, 258
**Thermostat**, 219, 244
**Thomson, J. J.**, 538
**Thomson, Sir William**, portrait, 205
**Thorium**, 556
**Threads**, 190
**Three-color printing**, 390; illustration, *Frontispiece*
**Time**, 15
**Timer**, 577
**Tornado**, 57
**Torque**, 509
**Torricelli**, 51; apparatus, 51; experiment, 51
**Total**, force, 22–24; reflection, 355
**Tourmaline**, 397; tongs, 397
**Tower**, leaning, 137
**Tractor**, 156–157
**Trade winds**, 262
**Train**, streamlined, 136
**Trajectory**, 149
**Trans-Atlantic radio telephone**, 551–553
**Transformation**, of energy, 172
**Transformer**, audio-frequency, 546–548; commercial, 518; efficiency of, 518; oscillation, 545–546; radio-frequency, 546–548; step-down, 517; step-up, 517
**Translucent objects**, 326
**Transmission**, of light, 326; of power, 197; of pressure, 51
**Transmission gears**, 573
**Transmitter**, 522
**Transmutation**, 560
**Transparency**, magnetic, 408
**Transparent objects**, 326
**Transportation**, 567
**Transverse waves**, 291
**Trap**, 84
**Treadle**, 199
**Triad**, major, 304
**Troposphere**, 60
**Tuner**, 546
**Tungar rectifier**, 527
**Tungsten lamp**, 474–475
**Tuning**, 546
**Tunnel**, Holland, 71; Lincoln, 72; ventilation of, 72
**Turbine**, advantages and disadvantages of, 276–278; Curtis, 276; illustrated, 277; Parsons, 276; Westinghouse, 276–277

**Turnbuckle,** 200
**Tyndall,** 230

**Ultramicroscope,** 89
**Umbra,** 326–327
**Undamped waves,** 541
**Underload circuit breaker,** 512
**Uniform motion,** 136
**United States weather maps,** 57–58
**Units,** electrical, 423; of area, 14; of capacity, 15; of energy, 171; of force, 110; of heat, 229, 230; of length, 14; of light, 330–331; of power, 168; of pressure, 110; of resistance, 423; of time, 15; of velocity, 135–136; of volume, 14–15; of weight, 111; of work, 165–167
**Universal gravitation,** 110
**Uranium,** 558

**Vacuum,** cleaner, 67–68; electrical discharge in, 531; in electric bulbs, 473; pans, 67; pump, 52, 65–66, 240–241; sound not transmitted by, 288; tube, 528, 545
**Valves,** controlled by, 273, 279; Corliss, 273; slide, 273
**Vapor heat,** 264
**Vaporization,** 237; heat of, 242; how to find heat of, 243
**Vapor pressure,** saturated, 239
**Varying field,** 515
**Velocities,** composition of, 149
**Velocity,** defined, 135; of alpha rays, 558; of beta rays, 558; of electric waves, 540; of light, 328–329; of sound in air, 290; of sound in other media, 290; of sound when temperature changes, 290
**Ventilation,** 259
**Venturi,** meter, 122; principle, 122
**Vernier scale,** 54
**Vertex,** 342
**Vibration,** air columns, 310; bells and plates, 312; complete, 291; forced, 299; frequency of, 291; kinds, 291; longitudinal, 291; of membranes, 313; of reeds, 312; of strings, 309; photographed, 316–317; single, 291; sympathetic, 299; transverse, 291
**Vibrograph,** 315
**Vinci, Leonardo da,** 366
**Virtual image,** 339
**Viscosity,** 98, 160
**Viscous,** 6
**Vise,** 190
**Vision,** binocular, 375; duration of, 376; nearest distance for distinct, 370
**Visual angle,** 365
**Vocal cords,** 313
**Voice,** 313
**Volt,** 423, 440
**Volta, Alessandro,** portrait, 434
**Voltage transformer,** 518
**Voltaic cell,** defects of, 437–438; defined, 434–435; dry, 439; grouping of, 443–444; local action in, 438; polarization of, 438–439; resistance of, 443; theory of. 437; types of, 439; voltage of, 442
**Voltmeter,** 481–483
**Volume,** 7; change of, 233

**Watch,** 219–220
**Water,** absorption of gases by, 102–103; city supply, 25–27; cooling, 568; density of, 15; displacement, 40; distillation of, 241; electrolysis of, 458–459; expansion of, 234; -gauge, 25; -head, 25; -heater, 265; heating system, 263; heat of fusion, 235; heat of vaporization, 242–243; motor, 196; poor conductor, 255; pressure, 19–21; refractive index of, 352; seeks its level, 24–25; sound transmitted by, 287–288; system, 25–27; total reflection in, 355; turbine, 197; wheels, 195
**Watt, James,** portrait of, 169
**Watt,** 168, 490
**Watt-hour,** 490
**Watt-hour** meter, 481, 490
**Waves,** audio-frequency, 307, 542; carrier, 541; damped, 540; ether, 539; heat, 205; light, 323–324; modulated, 541; pulsating, 543; radio, 540–543; radio-frequency, 307, 546; sound, 315–318; ultra-violet, 477, 538–539; undamped, 541; voice, 541
**Weather forecasting,** 57; long-range, 58b, 60
**Weather maps,** 57–58
**Wedge,** 188
**Weight,** 8; specific, 42
**Welding,** electric, 471
**Well,** artesian, 26
**Westinghouse, George,** portrait, 69
**Westinghouse,** brakes, 69–70
**Weston cell,** 440
**West Virginia,** 40
**Wheatstone bridge,** 491–492
**Wheel,** balance, 219, 220; steering, 571
**Wheel and axle,** 185–187
**Wheelbarrow,** 181
**Whirl,** electric, 429
**Whispering gallery,** 294
**Wilson, C. T. R.,** 564
**Wilson cloud chamber,** 563–564
**Winch,** 186, 201–202
**Windlass,** 186
**Windmill,** 195
**Winds,** trade, 261–262
**Wired radio,** 549
**Wireless diagram,** 546, 548
**Wiring,** parallel, 487; series, 485; uses of, 489
**Wollaston,** 393
**Woolworth Building,** 381
**Work,** defined, 163; in gas engine, 272; in human body, 271; in steam engine, 271; measured, 165; units of, 167; wasted, 270

**Worm wheel,** 195
**Wright, Orville,** portrait, 119
**Wright, Wilbur,** portrait, 119
**Wright Cyclone,** 121

**X rays,** nature of, 535–536; uses of, 535–537
**X-ray bulb,** 535–536

**Yard,** 13–14
**Yerkes telescope,** 371
**Young-Helmholtz,** theory, 389

**Zeppelin,** Graf, 81
**Zero,** absolute, 224–225
**Zonolith,** 257

QC 23 D88 1945 C-2
DULL CHARLES ELWOOD 1878-1947
MODERN PHYSICS

39641413 CURR HIST

*000023143787*

3
10
100 316
61 61 948
3900
62
375

DATE DUE SLIP

F255

The I
Dep
Th
E
T6G 2G5

DEC 2 3 1987